The Mass and Absorption Columns of Galactic Gaseous Halos

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Abstract

The galactic gaseous halo is a gas reservoir for the interstellar medium in the galaxy disk, supplying materials for star formation. We developed a gaseous halo model connecting the galaxy disk and the gaseous halo by assuming that the star formation rate on the disk is balanced by the radiative cooling rate of the gaseous halo, including stellar feedback. In addition to a single-temperature gaseous halo in collisional ionization equilibrium, we also consider the photoionization effect and a steady-state cooling model. Photoionization is important for modifying the ion distribution in low-mass galaxies and in the outskirts of massive galaxies due to the low densities. The multiphase cooling model dominates the region within the cooling radius, where \( t_{\text{cooling}} = t_{\text{Hubble}} \). Our model reproduces most of the observed high ionization state ions for a wide range of galaxy masses (i.e., O VI, O VII, Ne VIII, Mg X, and O VIII). We find that the O VI column density has a narrow range around \( 10^{12} \) cm\(^{-2} \) for halo masses from \( M_h \approx 3 \times 10^{10} \) to \( 6 \times 10^{12} \) M\(_\odot \), which is consistent with some but not all observational studies. For galaxies with halo masses \( \lesssim 3 \times 10^{11} \) M\(_\odot \), photoionization produces most of the O VI, while for more massive galaxies, the O VI is from the medium that is cooling from higher temperatures. Fitting the Galactic (Milky-Way) O VII and O VIII suggests a gaseous halo model where the metallicity is \( Z \approx 0.55 Z_{\odot} \) and the gaseous halo has a maximum temperature of \( 1.9 \times 10^6 \) K. This gaseous halo model does not close the census of baryonic material with \( R_{200} \).

Key words: galaxies: evolution – galaxies: halos – quasars: absorption lines – X-rays: galaxies

1. Introduction

Recently, more and more observational evidence have been found to show the importance of gaseous components (the circumgalactic medium, CGM) in galaxy halos (Anderson & Bregman 2010; Ménard et al. 2010; Werk et al. 2014; see the review of Tumlinson et al. 2017). These gaseous components surrounding the galaxy disk are formed during galaxy formation and are modified by various feedback processes, such as stellar feedback and active galactic nucleus (AGN) feedback (White & Frenk 1991). The existence of CGM also modifies the evolution of the galaxy by providing fresh materials for star formation (Kereš et al. 2005; Sancisi et al. 2008; Kereš et al. 2009) and by heating the materials accreted from the intergalactic medium (IGM) through gravitational potential release and accretion shock (Mo et al. 2010).

The existence of gaseous halos is also helpful to explain various observational issues, such as the missing baryon problem (wherein the baryonic fraction is significantly lower than the cosmic baryonic fraction of 0.16; Dai et al. 2010; McGaugh & Schombert 2015; Planck Collaboration et al. 2016). One solution is that the missing baryons remain in the galaxy but in an invisible phase (low density and high temperature), which could be the hot gaseous halo (Fukugita & Peebles 2006; Bregman & Lloyd-Davies 2007). Theoretical simulations have found that the cool gas (\( 10^4 \) K) in the early universe (\( z > 4 \)) is heated, becoming a warm-hot intergalactic medium (\( 10^5 \)–\( 10^7 \) K) during galaxy formation, which accounts for more than 30% of total baryons (Weinberg et al. 1997; Cen & Ostriker 1999).

The final temperature of these heating processes is around the virial temperature of the galaxy, which is determined by the galaxy halo mass. Massive galaxies have higher virial temperatures than low-mass galaxies, and the virial temperature of low-mass galaxies (\( M_h \sim 10^{11} \) M\(_\odot \)) is around \( 10^5 \) K, which is also the peak temperature of the radiative cooling curve and can lead to rapid cooling with a cooling timescale of \( < 1 \) Gyr. Therefore, whether the gaseous halo exists is a result of the competition between various heating processes and the radiative cooling, and this competition results in a multiphase medium in the gaseous halo (Oppenheimer et al. 2016).

Multiwavelength observations of both emission and absorption reveal media with different phases in the gaseous halo. The hot components in the gaseous halo can be detected in emission by direct X-ray imaging (Anderson & Bregman 2010; Bogdán et al. 2013; Goulding et al. 2016; Li et al. 2016) and in absorption or emission from high ionization state ions (e.g., O VII, Ne VIII, and Mg X; Nicastro et al. 2002; Savage et al. 2005; Miller & Bregman 2015; Qu & Bregman 2016). These studies found that the mass of the hot gaseous halo is comparable to the stellar mass of the galaxy, and about half of the total baryons are still missing. Some studies show that the hot gas may account for all missing baryons in the Milky Way (MW; Gupta et al. 2012; Nicastro et al. 2016a); however, they overestimate the emission measurement by more than one order of magnitude (Bregman et al. 2018; Li & Bregman 2018). Ultraviolet (UV) absorption line studies on low and intermediate ionization state ions show the existence of cool clouds in the halos, but the mass is model dependent, varying from 6% to 40% of the total baryon mass (Werk et al. 2014; Stern et al. 2016).

With a large amount of gas in the halo, radiative cooling may lead to a significant cooling flow onto the galaxy disk, which will be transformed into the stellar content of the disk through star formation (Sancisi et al. 2008). This astrophysical connection between the radiative cooling and star formation suggests that the cooling rate and the star formation rate (SFR) should be comparable to each other. Although the net cooling rate is also modified by heating from galactic feedback or accretion from the IGM, observations have shown that the
cooling rate is approximately the SFR for star-forming galaxies (with large scatter; Li et al. 2014).

In this paper, our starting point is the assumption that the SFR is balanced by the radiative cooling rate of the gaseous halo within the cooling radius. Then, we employ a set of assumptions for the gaseous halo—the density profile, the temperature distribution, hydrostatic and ionization equilibrium—and build up a halo model to connect the properties of the gaseous halo (i.e., mass and ion column density) to other galaxy properties (i.e., stellar mass and star formation rate). The details of the model assumptions are described in Section 2. In Section 3, we present the mass and column density of the gaseous halos, and their dependence on model parameters (e.g., stellar mass, SFR, or metallicity). The comparison with observations and their implications are discussed in Section 4; our results are summarized in Section 5.

2. Model

We consider a spherical volume-filling gaseous halo model to connect the galaxy properties with the gaseous halo properties. In this section, the employed assumptions will be described and discussed.

2.1. General Picture

During the formation of the galaxy, the accreted material is heated by the gravitational potential released through the accretion shock. Without radiative energy losses, the final temperature of a gravitationally self-bound system is the virial temperature that is determined by the total mass. However, a realistic gaseous halo suffers from radiative cooling, which is crucial for the formation of the galaxy disk.

Once the galaxy disk is formed, star formation leads to stellar feedback, injecting gas, dust, and energy into the gaseous halo. Stellar feedback affects the galaxy in several ways: stellar winds of massive stars; mass loss of asymptotic giant branch stars; and supernovae from either massive stars or degenerate stars (Zaritsky et al. 1994; Willson 2000; Scannapieco et al. 2008). Another main feedback channel is the central supermassive black halo that is in AGN phase, which injects ionizing photons and high-energy particles (Fabian 2012). These feedback processes can offset radiative cooling or reheat the cooled gas (Li et al. 2015). Although these processes are poorly resolved and implemented with different subgrid models in cosmological simulations, their effects on the galaxy evolution have been confirmed, showing that no single feedback channel can dominate across all galaxy masses (Vogelsberger et al. 2014; Schaye et al. 2015; Hopkins et al. 2017). However, the relative contributions for different processes are still controversial (Nelson et al. 2017; Suresh et al. 2017).

Besides the feedback from the galaxy disk, accretion from the IGM also provides additional energy to the gaseous halo as material falls deeper into the gravitational potential well. Then, the energy conservation of the gaseous halo leads to

\[ L_{\text{net,cl}} = L_{\text{rad}} - L_{\text{net,acc}} - L_{\text{fb}}, \]

where the subscripts “net, cl,” “rad,” “net, acc,” and “fb” denote the net cooling, the radiative cooling, the net accretion heating, and the feedback heating, respectively. For simplicity, we ignore the heating from the accretion of the IGM gas in our models, since the actual value of accretion heating depends on several uncertain factors—the accretion rate from the IGM, the accretion shock process, and the structure around the virial radius. However, an estimate shows that the contribution from accretion heating is not significant when the hot gaseous halo already exists. Assuming that the accreted material is virialized at the virial radius, the released gravitational potential energy is \( 2k_B T_{\text{vir}} \), which is slightly larger than the internal energy of the virialized halo of \( 3/2k_B T_{\text{vir}} \). In addition, the energy to ionize electrons from atoms will increase the internal energy by several tens of eV per atom, which is equivalent to a temperature of around \( 10^5 \text{--} 10^6 \text{K} \) (depending on the ionization state that is proportional to the virial temperature). Therefore, the energy used to ionize atoms cannot be transformed into internal energy, which decreases the net heating from the IGM accretion. Finally, we consider the net cooling rate that is only related to the radiative cooling and the heating due to galactic feedback.

The net cooling flux is related to the accretion flow since the cooled gas cannot be buoyant in the halo due to the gravitational potential. Once the gas from the halo is accreted onto the disk, it will interact with the disk interstellar medium or outflows launched from the disk, which leads to the disruption of the cool gas and the condensation of the hot gas (Marinacci et al. 2010; Scannapieco & Brüggen 2015). In addition, various processes are involved in this interaction, such as the disk dynamics and the thermal conduction, which lead to complex situations in different galaxies (Oosterloo et al. 2007; Armillotta et al. 2016; Zheng et al. 2017). These phenomena are beyond the scope of this paper; therefore, we assume that the accreted cold gas could be mixed with the existing ISM instantly to avoid detailed interactions between disk and halo gases.

Studies of the MW molecular clouds showed that the star formation timescale is comparable to the dynamical timescale of the cloud (~1--10 Myr), and the star formation efficiency is less than 2% (Larson 1981; Myers et al. 1986; Leroy et al. 2008). Considering the SFR of the MW to be \( \approx 1 M_{\odot} \text{yr}^{-1} \) (Robitaille & Whitney 2010), around 100\( M_{\odot} \) of gas per year should be transformed into star-forming molecular clouds since the lifetime of molecular clouds is short (~20 Myr; Larson 1981; Larson et al. 1994). The total atomic gas mass in the MW is around \( 7 \times 10^8 M_{\odot} \) (Nakanishi & Sofue 2016), which means that the atomic gas will be refreshed in around 70 Myr. Therefore, the timescale is around several 10^7 years to form stars using accreted cool gas from the gaseous halo. This timescale is comparable to the timescale of the current method to measure SFR of external galaxies (i.e., UV/IR), which measure the average SFR over 10^7 to 10^8 years (Madau & Dickinson 2014). In this sense, the measured net cooling flow mass has a physical connection to the measured SFR.

Cold mode accretion provides an additional gas origin besides hot mode accretion (the radiative cooling and accretion of the virialized halo), which requires the density to be at least one order of magnitude higher than \( n_{200} = (10^{-3} \text{--} 10^{-4} \text{cm}^{-3}) \) and the low temperature \( (10^2 \text{--} 10^3 \text{K}) \) for the gas to remain cool during accretion (Kereš et al. 2005). Cold mode accretion leads to cool gas filaments in the halo, directly connecting the disk and the IGM and transporting gases into the disk (Kereš et al. 2009). However, the existence of a hot ambient halo \( (T \approx T_{\text{vir}}) \) near hydrostatic equilibrium could destroy these cold gas filaments through mixing and interaction, which makes the
contribution from the cold mode accretion less than one-third that of the hot mode in the low-redshift universe \((z < 2); \) Nelson et al. 2013). Therefore, involving cold mode accretion will not break the balance between the cooling flow and the star formation, so we adopt the assumption that the net cooling rate is equal to the SFR.

Feedback processes must be included, as they will offset some of the radiative cooling. For a star-forming galaxy without a merger, the gas for star formation is originally from the gaseous halo, and the accretion from a gaseous halo is modified by the strength of stellar feedback (i.e., proportional to the SFR) when the redshift is low. Therefore, for a galaxy dominated by stellar feedback (with a dim AGN or without an AGN), the stellar feedback strength is proportional to the radiative cooling rate, which can be modeled as \(M_{\text{stellar, h}} = \alpha \Delta_{\text{rad, cl}}\). Then, a simple relationship between the SFR and the radiative cooling rate is

\[
\text{SFR} = \gamma \Delta_{\text{rad, cl}}, \tag{2}
\]

where \(\gamma = 1 - \alpha\) is smaller than unity to account for the heating by stellar feedback, and \(\Delta_{\text{rad, cl}}\) is the total radiative cooling rate of the gaseous halo. For simplicity, we assume that \(\gamma\) is unity for the following calculation; the effect of variations in this \(\gamma\) factor will be discussed in Section 4.

This relationship will be broken by several physical processes, such as feedback from an AGN or a starburst event. For AGN feedback, there is no direct connection with the SFR; therefore, there is no direct relationship between AGN feedback heating and radiative cooling. For merging galaxies that trigger starburst events, the connection between the SFR and the radiative cooling rate is not valid either, since the interaction between gases in the two galaxies triggers star formation, which is not related to the gaseous halo cooling. Therefore, Equation (2) is only applicable to stably evolving star-forming galaxies without powerful AGNs.

Therefore, in our model, the SFR and radiative cooling from the gaseous halo are tightly connected. This model is most applicable to field galaxies, rather than to group or cluster galaxies, which can be greatly affected by the intragroup or intracluster medium (Balogh et al. 1998). With these constraints, we adopt the conditions where the SFR is equal to the radiative cooling rate of the gaseous halo. The radiative cooling rate is limited within the cooling radius, where the cooling timescale is equal to the age of the universe (13.8 Gyr; Planck Collaboration et al. 2016) or to the cosmic epoch at a given redshift. In the following calculation, we use \(H_0 = 67.8\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_m = 0.308\), and \(\Omega_b = 0.0483\) (Planck Collaboration et al. 2016).

2.2. Galaxy and Gaseous Halo Properties

To construct sample galaxies, we adopt several empirical relationships. For a given stellar mass, we obtain the halo mass based on the stellar mass–halo mass (SMHM) relationship (Behroozi et al. 2013; Kravtsov et al. 2014). These two SMHM relationships diverge when \(M_h > 10^{11.5}\) \(M_\odot\), and Kravtsov et al. (2014) have a higher stellar mass than Behroozi’s relationship. At the halo mass of \(10^{13.5}\) \(M_\odot\), the stellar mass difference is around 0.5 dex. We choose Kravtsov’s SMHM relationship, since it describes the case that is more similar to the MW, where a \(\approx 2 \times 10^{12}\) \(M_\odot\) halo hosts a \(5-8 \times 10^{10}\) \(M_\odot\) galaxy disk. Once the halo mass is determined, the virial radius and the virial temperature are calculated as

\[
R_{\text{vir}} = R_{200} = \frac{M_h}{4\pi \Delta_{\text{vir}} \rho_{\text{crit}}/3},
\]

\[
V_c^2 = \frac{GM_h}{R_{\text{vir}}} = 100H_0^2 R_{\text{vir}}^2,
\]

\[
T_{\text{vir}} = \frac{\mu m_p V_c^2}{2 k_B},\tag{3}
\]

where \(\Delta_{\text{vir}} = 200\) is the collapse factor, and \(\rho_{\text{crit}} = 3H_0^2/8\pi G\) is the cosmic critical density. The quantities \(R_{\text{vir}}\) and \(T_{\text{vir}}\) are the input parameters of our models and can be varied by introducing additional factors (as in the model of the MW in Section 4.5). Therefore, the choice of the SMHM relationship does not affect our results significantly.

The star formation rate can be inferred using the star formation–stellar mass plane (Renzini & Peng 2015; Morselli et al. 2016).

\[
\log(\text{SFR}) = (0.72 \pm 0.02)\log M_* - 7.12,\tag{4}
\]

in the stellar mass range of \(M_* > 10^{10.5} - 10^{11.25}\) \(M_\odot\). Therefore, we set the range of the halo mass to \(10^{10.5} - 10^{13.5}\) \(M_\odot\). The star formation also has a dependence on the redshift (Pannella et al. 2009):

\[
\text{SFR} \approx 270 \frac{M_*}{10^{11} M_\odot} \left(\frac{t}{3.4 \times 10^9 \text{ years}}\right)^{-2.5} M_\odot / \text{years},\tag{5}
\]

where \(t\) is the cosmic epoch. This relationship can be rewritten as a dependence on the redshift directly, \(s\text{SFR} \propto (1+z)^3\) at \(z < 2\) (Lilly et al. 2013).

The structure of the gaseous halo is also fixed to reduce the degrees of freedom, and we adopt the \(\beta\)-model for gaseous halos for all galaxies with different masses, which has the density profile

\[
\rho(r) = n_0 \left(1 + \frac{r^2}{r_c^2}\right)^{-3\beta/2},\tag{6}
\]

where \(n_0\) is the normalization parameter, and \(r_c\) is the core radius. Normally, core radii for galaxies are small and cannot be modeled for isolated galaxies (Li et al. 2016). Then, we rewrite the profile as

\[
\rho(r) = n_0 r_c^{3\beta} r^{3\beta},\tag{7}
\]

which is valid for \(r \gg r_c\), and then the degeneracy of \(n_0 r_c^{3\beta}\) will not be broken. X-ray imaging studies on nearby massive galaxies showed that the \(\beta\)-factor is around 0.5 within the radius \(\leq 0.5\) kpc (Anderson et al. 2016). Recently, the Circum-Galactic Medium of MASSive Spirals (CGM-MASS) project showed that \(\beta\) is a constant \(= 0.4\) extended to around half of the virial radius \((\approx 200\) kpc for massive star-forming spiral galaxies; Li et al. 2018). Therefore, we adopted \(\beta\) as a constant over the entire radius range for one gaseous halo, but \(\beta\) can be varied for different models.

Since the total mass of the \(\beta\)-model is not convergent with increasing radius, we need to set the radius range for this model. In the inner region, other physical processes occur (e.g., the interaction with disk gases); therefore, the hydrostatic assumption is broken, and the \(\beta\)-model may not be applicable.
This radius is set by the competition between the free-fall timescale and the radiative cooling timescale, which is around 5–10 kpc using the radiative cooling timescale of the MW from Miller & Bregman (2015). Massive galaxies have larger inner radii that can be larger than 10 kpc, but our model does not show a significant dependence on the innermost radius. From 5 kpc to 10 kpc, the mass of the gaseous halo is increased by up to 15%, which is only for the most massive galaxies ($M_\odot > 10^{12} M_\odot$) due to their small cooling radii. For $L^*$ galaxies, this change is smaller than 10%; therefore, we fix the innermost radius to 5 kpc for all galaxies. For the outer region, the maximum radius is set to the virial radius for a given halo mass, which means that the density goes to zero at the virial radius. However, it has been shown that the massive system (galaxy cluster) could have detectable gas reaching $R_{200}$, which implies that the gaseous component could extend beyond the virial radius (Baldi et al. 2012). Therefore, this assumption may not be correct; however, there are no other means to set an unbiased boundary condition.

The normalization parameter $n_0$ is calculated based on the assumption that the SFR is equal to the radiative cooling rate:

$$\text{SFR} = \int_{5 \text{ kpc}}^{\min(R_{200}, R_{\text{MM}})} \frac{\overline{\alpha}(r)n^2(r)}{\tau(r)} \mu m_p 4 \pi r^2 dr,$$  

where $\overline{\alpha}(r)$ is the average cooling emissivity, while $\tau(r)$ is the average internal energy at a given radius, defined as

$$\overline{\alpha} = \int_{T_{\text{min}}}^{T_{\text{max}}} M(T)n(T)\lambda(T) dT,$$

$$\tau = \int_{T_{\text{min}}}^{T_{\text{max}}} M(T) \frac{3}{2} k_B T dT.$$  

$M(T)$ is the mass distribution depending on the temperature, which has the normalization of $\int_{T_{\text{min}}}^{T_{\text{max}}} M(T) dT = 1$. Here, we also assume that the average mass of particles ($\mu$) is 0.59 for the temperature range considered ($T > 10^{4.5}$ K), since this value is dominated by the ionization state of hydrogen, which is almost completely ionized in this temperature range. The choice in the radiative cooling model will be discussed in the following section.

The radial dependence of temperature is still observationally poorly constrained for isolated galaxies. X-ray studies of galaxy clusters showed that the temperature variation is less than one order of magnitude within $R_{200}$ (Baldi et al. 2012). For isolated star-forming galaxies, Anderson et al. (2016) showed that NGC 1961 also has a small variation, but only out to ~50 kpc. Here, we assume that the temperature has no radius dependence.

### 2.3. Cooling Emissivity

The radiative cooling rate is directly affected by the emissivity, which has a dependence on the temperature, the density, and the metallicity. For the temperature range of a gaseous halo ($10^{4.5} - 10^7$ K), the radiative cooling is dominated by lines of various ions. Therefore, for a given temperature and density, the ionization state of different ions can be determined, and the cooling rate is calculated involving the metallicity. Here, we assume that the gaseous halo is in ionization equilibrium, and consider two ionization processes—collisional ionization and the modification due to photoionization.

For collisional ionization equilibrium (CIE), we adopt the emissivity calculated using CHIANTI (version 8.0.6; Del Zanna et al. 2015). In this calculation, the metallicity is set to 0.1 $Z_\odot$, 0.3 $Z_\odot$, 1.0 $Z_\odot$, and 2.0 $Z_\odot$, and the solar metallicity of $Z_\odot = 0.0142$ is adopted from Asplund et al. (2009).

The photoionization due to the ultraviolet background (UVB) can modify the ionization distribution of different elements (Wiersma et al. 2009), and the photoionization model is employed to model the low- and intermediate ionization ions in intervening systems (Savage et al. 2014; Werk et al. 2014). Also, the high ionization state ions might be photoionized at low densities of $\lesssim 10^{-5}$ cm$^{-3}$, which is the expected density in the outskirts of gaseous halos (Hussain et al. 2015, 2017). Therefore, we include the photoionization from the UVB to compare with the pure collisional ionization mode.

Galaxies also provide part of the ionizing flux to photoionize the CGM or nearby IGM, which is known as the escaping ionizing flux. The escape fraction is believed to be large ($\gtrsim 10\%$) in the early universe ($z > 6$) to contribute to the reionization (Mitra et al. 2013), while studies of the low-redshift IGM ($z < 2$) found that the escape fraction is several percent (Khaire & Srianand 2015). The small escape fraction implies that those ionizing photons mainly affect the innermost ~50 kpc region of the gaseous halo, thus we ignore ionizing photons from the galaxy disk (Suresh et al. 2017).

For the photoionization equilibrium (PIE), we adopt the calculation from Oppenheimer & Schaye (2013), who tabulated results for different redshifts, densities, and temperatures. Several UVB models have been provided, and we choose the UVB from Haardt & Madau (2012) in our models. In this database, the authors also include the cosmic microwave background (CMB), with a dependence on the redshift. The existence of the CMB provides a large number of low-energy photons, which can be heated by inverse Compton scattering, thereby cooling the high-temperature electrons.

In Figure 1, we show the comparison between the CIE and PIE cooling curves. High-energy photons from the UVB photoionize low ionization state ions to higher states, suppressing the cooling in the low-temperature region. Due to the lack of H I, the first peak around $2 \times 10^4$ K is missing. Photoionization also changes the ionization fraction of metals and contributes to the radiative cooling, suppressing low ionization state cooling (e.g., C II and O II) and increasing high ionization state cooling (e.g., O VI). Therefore, the cooling emissivity is lower in the low-temperature regime for the PIE model than for the CIE model. Inverse Compton cooling due to CMB dominates the high-temperature and low-density gas. The emissivity of inverse Compton scattering is proportional to $n T$, while the free–free emission has the dependence $n^2 T^{1/2}$. Therefore, there is always a critical combination of temperatures and densities above which inverse Compton cooling is dominant. However, in the low-redshift universe ($z < 2$), the number density of CMB photons is sufficiently low so that gases have a cooling timescale longer than the Hubble timescale. Therefore, the effect due to the CMB can be ignored for the low-redshift ($z < 2$) universe. The effect of the radiative cooling model will be described in detail in Section 3.
upward-pointing triangles show the cooling curve at

\[ T \text{(K)} \]

The dotted line has a density of \( 10^{20} \text{cm}^{-3} \), while the upper limit of the density is the luminosity at a given temperature. CIE cooling curves with metallicities of 0.1 \( Z_{\odot} \), 0.3 \( Z_{\odot} \), 1.0 \( Z_{\odot} \), and 2.0 \( Z_{\odot} \) are shown in dotted, dashed, solid and dotted–dashed lines, respectively. With these temperature limits, which are related to the galaxy mass, this function can be normalized as \( \int_{T_{\text{min}}}^{T_{\text{max}}} M(T)dT = 1 \) to obtain the mass distribution \( M(T) \).

Figure 2. Unnormalized mass distribution for cooling gas as a function of temperature. CIE cooling curves with metallicities of 0.1 \( Z_{\odot} \), 0.3 \( Z_{\odot} \), 1.0 \( Z_{\odot} \), and 2.0 \( Z_{\odot} \) are shown in dotted, dashed, solid and dotted–dashed lines, respectively. With these temperature limits, which are related to the galaxy mass, this function can be normalized as \( \int_{T_{\text{min}}}^{T_{\text{max}}} M(T)dT = 1 \) to obtain the mass distribution \( M(T) \).

Figure 1. Comparison between the cooling curve for pure collisional ionization (CIE) and with the modification from photoionization (PIE). The cooling curves in CIE have metallicities of 1 \( Z_{\odot} \) (solid line) and 0.3 \( Z_{\odot} \) (dashed line). The three PIE cooling curves all have the same metallicity of 0.3 \( Z_{\odot} \). The dotted line has a density of \( 10^{-1} \text{cm}^{-3} \), the typical density of the inner gaseous halo at \( z = 0 \), while the dashed–dotted line has a lower density of \( 10^{-6} \text{cm}^{-3} \), typical of the density in the halo outskirts at the same redshift. The upward-pointing triangles show the cooling curve at \( z = 1 \) with a density of \( 10^{-8} \text{cm}^{-3} \).

### 2.4. Temperature Dependence of the Mass Distribution

Multiphase gas in gaseous halos have been detected by various observations (Nicastro et al. 2002; Danforth & Shull 2008; Anderson et al. 2013; Werk et al. 2013; Savage et al. 2014; Qu & Bregman 2016). Unfortunately, obtaining an accurate distribution of the multiphase medium by mass remains a challenge both observationally and theoretically (e.g., the divergence in O VI abundance; Oppenheimer et al. 2016; Suresh et al. 2017). Therefore, for the simplest model, we assume that the gaseous halo is a single-phase medium at the virial temperature.

We also consider a stable cooling model, which is a time-independent solution. In this model, we assume that the mass cooling rate is the same at all temperatures,

\[
L(T) = \Lambda(T)n^2(T) \frac{M(T)}{\mu m_p n(T)} = \text{const.,}
\]

where \( L(T) \) is the luminosity at a given temperature \( T \) and \( M(T) \) is the mass distribution dependence on the temperature. Another assumption is the pressure balance, which implies \( n(T) \propto 1/T \). Thus, the mass distribution is

\[
M(T) = \frac{T}{\Lambda(T)} \int_{T_{\text{min}}}^{T_{\text{max}}} T \frac{dT}{\Lambda(T)}
\]

where the temperature upper limit \( (T_{\text{max}}) \) is set to the virial temperature, while the lower limit is fixed to \( 10^{4.5} \text{K} \), below which forbidden lines dominate the cooling, fixed with dust and molecules. An example of \( M(T) \) without normalization is shown in Figure 2.

Our model does not include all relevant physics that occur in galaxy halos (e.g., thermal instabilities), but it allows us to explore a wide range of parameter space and to identify robust results. Detailed calculations show that the stable cooling model can be applicable for the cooling in the temperature range of \( 10^3 \text{K} \) to \( 10^6 \text{K} \) in stellar feedback dominated galaxies (Thompson et al. 2016). Their breaking of this cooling assumption in the high-temperature range is mainly because they consider the hot gas from the stellar feedback, which softens the assumed boundary condition that the high-temperature gas can be supplied infinitely. However, in the gaseous halo scenario, this condition could be satisfied when a gaseous halo with a hot and long radiative-cooling timescale exists.

### 3. Results

We calculate three models with different cooling models and temperature distributions—CIE: the single-temperature collisional ionization model; PIE: the single-temperature photoionization model; and TCIE: the collisional ionization model with the mass distribution described in Section 2.4. In this section, we show our main results for these models on the gaseous halo mass and the ion column density.

#### 3.1. Fiducial Galaxies

There are four factors affecting the properties of the gaseous halo in our simplified models—the metallicity \( (Z) \), the specific star formation rate \( (\text{sSFR}; \text{defined as } \text{SFR} / M_\odot) \), the slope of the \( \beta \)-model \( (\beta) \), and the redshift \( (z) \). Based on these four dimensions, we have fiducial galaxies defined as \( \log M_\odot = 10.5 - 13.3 \), \( Z = 0.3 \ Z_\odot \) (cosmic metallicity), \( \text{sSFR} = 10^{-10} \text{yr}^{-1} \) (star-forming), \( \beta = 0.5 \) (hydrostatic equilibrium structure), and \( z = 0 \). For each modeled gaseous halo, we calculate the gaseous halo mass (enclosed from 5 kpc to the virial radius) and the cooling radius. The calculation results are shown in Figure 3.

For the fiducial case, all three models have gaseous halo masses that are smaller than the corresponding stellar masses around the (sub-)\(L^*\) galaxies. The largest difference of \( \approx 0.5 \text{dex} \) occurs at sub-\(L^*\) galaxies \( (M_\star \approx 4 \times 10^9 M_\odot) \). Overall, the CIE model shows convergence with the TCIE model in the low-mass region and converges with the PIE model for massive galaxies. With the halo mass decreasing, the temperature range for TCIE \( (T_{\text{min}} = 3 \times 10^4 \text{K}) \) is also decreasing, which leads to the similarity with CIE. Both
collisional ionization models have lower-mass gaseous halos than the PIE model because they have a higher radiative emissivity in the low temperature, and the photoionization due to the UVB can support a relatively more massive halo for low-mass galaxies.

In the massive galaxy range, radiative cooling is reduced at high temperatures, which results in a massive gaseous halo, consistent with theoretical expectations (Mo et al. 2010). These halos are supported by their buoyancy even for the PIE model. The convergence between CIE and PIE is due to the higher density in massive galaxies—in the inner region (inside of the cooling radius), the average density is higher than $10^{4} \text{ cm}^{-3}$. This high density corresponds to the low-ionization parameter ($U = n_{\text{H}}/n_{\text{H}}^{\text{ion}}$), indicating the weakening of photoionization. As shown in Figure 1, the CIE cooling is consistent with the PIE cooling with a density of $10^{4} \text{ cm}^{-3}$. TCIE has a lower-mass gaseous halo than CIE or PIE, due to its higher average emissivity since this model always has low-temperature gas with a higher radiative emissivity.

Overall, the cooling radius varies only modestly over the halo mass range in each model. Specifically, the variation is less than one order of magnitude, and this variation corresponds to the changes in the average emissivity. With the higher emissivity, the cooling radius is larger; however, the changes in the cooling radius is smaller than the emissivity changes. Meanwhile, the cooling radius shows a similar convergence to the gaseous halo mass between CIE and TCIE for low-mass galaxies, and between CIE and PIE for massive galaxies.

3.2. The Effect of Galaxy Properties

By changing the four parameters ($Z$, sSFR, $\beta$, and $z$), we show the effect of these parameters on the resulting hot halo and column densities. For each parameter, we have four choices: the metallicity, $0.1Z_{\odot}, 0.3Z_{\odot}, 1Z_{\odot}$, or $2Z_{\odot}$; the specific SFR, $10^{-9} \text{ yr}^{-1}, 10^{-10} \text{ yr}^{-1}, 10^{-11} \text{ yr}^{-1}$, or $10^{-12} \text{ yr}^{-1}$; the $\beta$ parameter, $0.3, 0.4, 0.5,$ or $0.6$; and the redshift, $0, 0.2, 0.5,$ or $1$. In Figure 4, we show the change corresponding to these parameters as the ratio between the different models and the fiducial model.

The high metallicity increases the cooling emissivity, which reduces the normalization parameter in the $\beta$-model, and subsequently, the halo mass. With the variation of metallicity in the range $0.1-2.0Z_{\odot}$, the change of the gaseous halo mass is less than a factor of 5, whereas the change of metallicity is a factor of 20. This implies that lower-metallicity gaseous halos have a lower total metal mass to account for the same cooling rate. The cooling radius of the CIE and TCIE models has a positive dependence on the metallicity due to the increase of emissivity. However, the inclusion of photoionization shows a similar cooling radius for different metallicities in the low-mass end, which indicates that the radiative cooling due to the low-ionization metal ions is suppressed by photoionization.

An sSFR of $10^{-11} \text{ yr}^{-1}$ is used as a boundary between a star-forming galaxy and a quiescent galaxy, while normal star-forming galaxies have sSFR values of around $10^{-10}$ (Renzini & Peng 2015). By increasing the sSFR, the total radiative cooling rate is increased, which means that a massive gaseous halo is needed. For CIE and TCIE, this effect is almost constant over all mass regions, and PIE shows a similar tendency in the high-mass region ($>10^{12} \text{ M}_{\odot}$). However, for low-mass galaxies, PIE models with different sSFR values show a significant convergence of the gaseous halo mass, which indicates that the effect of a changing sSFR is not as large as in CIE or TCIE. The reason for these phenomena is that there are two ways to increase the radiative cooling rate—through either higher density or higher emissivity. In the CIE and TCIE models, the emissivity cannot be increased when the temperature distribution is fixed. Therefore, the only way to raise the cooling rate is by increasing the density, which makes the density proportional to the square root of the sSFR for all halo masses. In the PIE model, the emissivity has a dependence on the density as shown in Figure 1. Within the cooling radius, the density is higher than $10^{4} \text{ cm}^{-2}$, and the PIE cooling curve does not deviate from the CIE cooling curve significantly in the temperature range of $\approx 10^{5.5}-10^{6} \text{ K}$. For galactic gaseous halos with these temperatures ($M_{\text{h}} > 10^{12} \text{ M}_{\odot}$), the emissivity shows...
galaxy, which has parameters of smaller change in the density to account for the high sSFR.

Density itself but also increases the emissivity, which leads to an increase in the cooling rate by the squared dependence on the density. Therefore, in the PIE model, the high density not only increases the cooling rate by the squared dependence on the density itself but also increases the emissivity, which leads to a smaller change in the density to account for the high sSFR.

The variation of the sSFR is equivalent to changing the \( \gamma \) factor with the sSFR unchanged. As an example, sSFR = \( 10^{-9} \) with \( \gamma = 1 \) is the same model as sSFR = \( 10^{-10} \) but with \( \gamma = 0.1 \). Therefore, our models show that the gaseous halo mass has a square root dependence on the inverse \( \gamma \) factor.

With a larger \( \beta \), the gas is more concentrated in the central region (at the same gas mass), which leads to the higher emissivity. Since the mass is linearly dependent on the density, the larger \( \beta \) results in a smaller gaseous halo mass. Due to the concentrated emission, the cooling radius also decreases as \( \beta \) increases. The effect of a larger \( \beta \) also has a dependence on the halo mass—with a more massive halo, the ratio of masses is larger, as shown in Figure 4. This correlation occurs because the massive galaxy has a relatively small cooling radius compared to the virial radius, and the flat \( \beta \)-model can host more mass in the region beyond the cooling radius.

A higher redshift can affect the gaseous halo in three ways—through the higher gas density, the younger universe age, and the more intense cosmic background. First, due to the expansion of the universe, the higher-redshift universe has a higher density, which leads to the smaller virial radius, and hence higher virial temperature. Second, the younger universe age at higher redshift leads to a shorter cooling timescale, which reduces the cooling radius and the total cooling rate within this radius. Since the CIE and PIE models have no photoionization involved, these two models are only affected by these two factors. The gaseous halo mass has an anticorrelation with the cooling emissivity of the gas, but the emissivity is a result of a competition between two factors—the increasing emissivity due to the higher density and the change due to the virial temperature. Together, these complex effects lead to small variations of the gaseous halo mass, which reflect the shape of the cooling curve (i.e., the bump around \( T_{\text{vir}} \approx 10^{5.5} \) K, also the peak of the cooling curve). For the cooling radius, the effect is clear that the higher redshift leads to a smaller cooling radius. The cooling radius of a \( z = 0 \) galaxy is about 1.5 times larger than the same mass galaxy at \( z = 1 \) galaxies.

The cosmic background includes two parts—the UVB and the CMB. As stated in Section 2.3, inverse Compton cooling is negligible in the low-redshift universe \((z < 6)\), but the UVB changes the ionization state distribution, leading to reduced radiative cooling in the low-temperature region. Therefore, for the low-mass galaxies \((M_{\text{h}} \lesssim 10^{11.3} M_{\odot})\), a more massive gaseous halo is required to account for the same SFR with the UVB increasing at the higher redshift, which results in the mass ratio being slightly larger than 1. For the high-temperature end, the PIE model converges with the CIE model, which is expected.

### 3.3. The Ion Column Densities

With the calculated density profile and the temperature distribution, we calculate the column density for the ions of interests (mainly high ionization state ions), which are more...
common in the hot ambient medium. For the CIE and TCIE models, we adopt the ionization distributions from Bryans et al. (2006), which only have a dependence on the temperature. The PIE ionization fraction is adopted from Oppenheimer & Schaye (2013), which is tabulated based on the redshift, the metallicity, the density, and the temperature.

For the TCIE model, we calculate the average ionization fraction using

$$f_\text{av} = \frac{1}{T_{\text{max}} - T_{\text{min}}} \int_{T_{\text{min}}}^{T_{\text{max}}} f_i(T) M(T) dT. \quad (13)$$

Here, we assume that multiphase medium has similar covering factors of around 1, which implies that the multiphase medium is well-mixed. This assumption should be good for high ionization state ions. Werk et al. (2013) shows that intermediate ionization ions (i.e., C III, Si III, Si IV) and high ionization ions (i.e., O VI) have comparable covering factors of around 0.8, except that for O VI seems to be lower in quiescent galaxies. However, this is probably caused by quiescent galaxies that are usually massive galaxies with higher virial temperatures (Oppenheimer et al. 2016).

In Figure 5, we compare the three models (CIE, TCIE, and PIE), showing ion column densities for star-forming galaxies (i.e., $Z = 0.3 Z_\odot$, $z = 0$, sSFR = $10^{-10}$ yr$^{-1}$, and $\beta = 0.5$). To show the dependence on the stellar mass, we fix the impact parameter to be 0.3 $R_{\text{vir}}$, which is a typical impact parameter in the COS-Halos program and also leads to a similar column density for ions observed in the MW from the Sun. Similar to the result of the gaseous halo mass, CIE and PIE shows the convergence of H I column densities from $M_h = 4 \times 10^{13} M_\odot$ and above, which indicates that the cooling emissivity is almost the same. However, other ions do not show the same similarity, which indicates that the ionization fractions are not similar. Only the most massive halos ($M_h > 10^{13} M_\odot$) have similar ionization fractions for CIE and PIE due to the relatively higher density. In low-mass galaxies (on the left side of the ionization peak for the different ions), PIE leads to extended tails for high ionization state ions (e.g., O VI and O VII) because of the low density.

Figure 5. Comparison of the ion column density between the three models, CIE, PIE, and TCIE at $z = 0$, which are shown in dashed, dotted, and solid lines, respectively. Different ions are shown in different colors: blue—hydrogen (reduced by a factor of 10$^3$); green—O VI; red—O VII; yellow—O VIII; cyan—Ne VIII; and magenta—Mg X. Left panel: the column density dependence on the halo mass. The galaxy sample is the fiducial galaxy locus, and the impact parameter is fixed to 0.3 $R_{\text{vir}}$. Right panel: the column density dependence on the impact parameter for the galaxy with $M_h = 7 \times 10^{10} M_\odot$, and $\text{SFR} = 3 M_\odot$ yr$^{-1}$; $Z = 0.3 Z_\odot$, and $\beta = 0.5$.

Compared to CIE or PIE without cooling temperature distributions, TCIE does not show the shape of the ionization fraction function directly, but it shows a flattened peak for high ionization state ions. For O VI and O VII, the column peaks are $\gtrsim 10^{14}$ cm$^{-2}$ and $7 \times 10^{15}$ cm$^{-2}$, respectively. The column density of O VI is higher than $10^{13.5}$ cm$^{-2}$ over a halo mass range of $2 \times 10^{11} M_\odot$ to $4 \times 10^{12} M_\odot$. Ne VIII and Mg X show comparable flattened column density distributions in the range of $10^{13.5} - 10^{14}$ cm$^{-2}$, while Ne VIII occurs in lower-mass galaxies compared to Mg X.

To show the ion column density dependence on the impact parameter, we choose a MW-like galaxy with $M_h = 7 \times 10^{10} M_\odot$, SFR = $3 M_\odot$ yr$^{-1}$, $Z = 0.3$, $\beta = 0.5$, and $z = 0$. In the CIE and TCIE models, the ionization fraction does not have a dependence on the density, so the average ionization fraction has no dependence on the impact parameter. Therefore, all columns follow the general radial decrease of the $\beta$-model. For the PIE model, the significant flattening of O VIII in the small impact parameter region shows that the ionization fraction in the inner region is somewhat larger than that in the outer region, where the photoionization generates more O VIII (Oppenheimer & Schaye 2013). The turnover point is about the half of the virial radius, where about half of O VIII is produced beyond this radius.

We consider the redshift dependence of the PIE model in Figure 6, which is otherwise similar to Figure 5. At higher redshifts, the more intense UVB leads to a stronger tail of high ionization state ions in low-mass galaxies. Also, high ionization ions (e.g., O VIII) show peaks at a lower halo mass for the high-redshift galaxy, as the O VIII column density peak moves from $M_h \approx 7 \times 10^{12} M_\odot$ ($z = 0$) to $M_h \approx 4 \times 10^{12} M_\odot$ ($z = 1$). This is mainly due to the increasing virial temperature at higher redshifts. For these higher virial temperatures, the O VIII column density is no longer flat in the small impact parameter region at $z = 1$, which means that the ionization of O VIII is no longer dominated by the photoionization. Although the high density in the inner region still reduces the ionization fraction of O VIII, a significant amount of O VIII is produced in the inner region through collisional ionization.
3.4. Galaxies with the SFR Main Sequence

Using the relationship between the SFR and the stellar mass (Morselli et al. 2016), we generate a set of galaxies with typical SFRs and calculate the ion column densities, showing the result in Figure 7. The sSFR has a weak dependence on the stellar mass as sSFR \( \propto M_{\star}^{-0.28} \), so the changes are modest compared to Figure 3, where the sSFR is constant for different galaxies. Due to the high sSFR of low-mass galaxies \( M_{\star} < 10^{11} M_{\odot} \), these galaxies have higher normalization factors in the \( \beta \)-model and gaseous halo masses. The gaseous halo mass at the high-mass end \( M_{\star} \approx 10^{13} M_{\odot} \) is decreased by a factor of two, due to the small sSFR. The cooling radius has a moderately narrow range of 50 kpc to 200 kpc as a function of the halo mass for a given model. Therefore, the increasing \( R_{\text{vir}} \) leads to a decrease of the relative cooling radius in units of \( R_{\text{vir}} \). Compared to Figure 3, the cooling radius in the low-mass range is raised until \( M_{\star} \approx 10^{11.5} M_{\odot} \), while it is suppressed for the massive galaxy, corresponding to the change in the sSFR. For dwarf galaxies \( M_{\star} \lesssim 5 \times 10^{11} M_{\odot} \), the entire gaseous halo is radiatively cooling in the \textit{CIE} and \textit{TCIE} models, while the \textit{PIE} model always shows the cooling radius to be smaller than the virial radius.

We also consider the SFR modification on the ion column density, shown in Figure 8. Due to the more massive gaseous halo of low-mass galaxies, the total hydrogen column density is increased significantly, while high ionization state ions (e.g., O VII and O VIII) changes within a factor of 1.5. The massive galaxy shows ions with column densities slightly smaller than Figure 5. Overall, the sSFR dependence on stellar mass does not change the phenomena illustrated by the fixed sSFR models, such as the convergence between models.

4. Discussion

Currently, modeling gaseous components in halos often assumes a single-temperature \textit{CIE} model or a photon-heated \textit{PIE} model (Stocke et al. 2013; Werk et al. 2014; Miller & Bregman 2015; Nicastro et al. 2016a; Faerman et al. 2017). Improvements in such assumptions are warranted by
observations that indicate the presence of a multiphase medium and temperature variations over different radii (Anderson et al. 2016; Tumlinson et al. 2017). However, both of these two temperature issues are not well constrained observationally—there is no universal temperature distribution for multiphase gas or a universal radial dependence of the temperature (Anderson et al. 2016; Bogdán et al. 2017; Tumlinson et al. 2017).

Besides the gas temperature, the contribution by photoionization is controversial regarding its effect on high ionization state ions. The photoionization model is employed to explain the low and intermediate ionization state absorption system seen against the UV spectrum of background quasi-stellar objects (QSOs; Werk et al. 2014). High ionization state ions (e.g., O VI and Ne VIII) are normally explained by the collisional ionization model (Savage et al. 2005; Narayanan et al. 2012; Meiring et al. 2013; Pachat et al. 2017), while they are also possible to be modeled by photoionization (Hussain et al. 2015, 2017).

In the last decade, the effects of photoionization and radiative cooling have been considered in theoretical calculations (Wiersma et al. 2009; Oppenheimer & Schaye 2013; Gnat 2017). Benefiting from these numerical calculations, we apply two improvements to the modeling of gaseous halos—the photoionization modification and the radiative cooling multiphase medium. These two improvements change the radiative cooling rate of the gaseous halo, and subsequently the mass of the gaseous halo, and the ions hosted by the halo. In this section, we compare our models with observations and theoretical simulations, and discuss implications and limitations.

4.1. The Most Applicable Models

In our gaseous halo model, we consider the modification of the photoionization and the effect of the radiatively cooling multiphase medium separately. In general, photoionization mainly affects low-temperature or low-density regions. In the context of a gaseous halo, low-temperature gas is most common in low-mass galaxies, while low-density gas is in the outskirts of gaseous halos. Meanwhile, radiative cooling mainly occurs within the cooling radius, where the density is high enough for effective radiative cooling. However, these modifications have several limitations, which should be considered when one evaluates the applicability of these models.

For the photoionization of the gaseous halo, there are two main limitations—the lack of ionizing photons from the host galaxy and the lack of radiation transfer inside the halo. First, we only employ the UVB to supply ionizing photons; however, it is not the only source of high-energy ionizing photons. The host galaxy also provides ionizing radiation from star formation or soft X-rays from shock-heated gases due to stellar winds and supernovae. Assuming an escape fraction of unity for soft X-rays, Suresh et al. (2017) show that the impact of the photoionization due to the host galaxy is limited to the inner 50 kpc traced by the O VI. Typically, the escape fraction is only several percent for low-redshift galaxies (z < 2; Grimes et al. 2009; Khaire & Srianand 2015), which indicates that the escaping ionizing flux of the galaxy dominates the innermost region within the cooling radius. Second, ionizing UVB photons will be diluted by the absorption inside the gaseous halo, which leads to the suppression of photoionization with decreasing radius. The decrease in photoionization means that the medium in the inner region is more likely to be collisionally ionized. Therefore, the UVB-only PIE model is more likely the case for the outer region of massive halos.

We assume a time-independent cooling model for the multiphase radiatively cooling medium, where the mass cooling rate is constant over all temperatures. This model has two assumptions—the gases at different temperatures are “well-mixed” and the hot medium can always be supplied to keep the cooling time independent. The first assumption means that the multiphase ionic structure should have a physical connection (mixture) at various temperatures to keep the same mass cooling rate, and the cooling is only due to the radiative losses of the entire gaseous halo. However, some of the physical aspects surrounding the cooling, which are related to various processes aside from pure radiative cooling—the galactic fountain, the accretion from the IGM, and even the tidal effect due to nearby galaxies (Bregman 1980; Kwak & Shelton 2010; Marinacci et al. 2010; Gnat 2017)—are still uncertain. These processes introduce perturbations to the gaseous halo, which lead to denser regions and possible thermal instabilities that might enhance the radiative cooling (Armillotta et al. 2016, 2017). These processes cannot be investigated in our analytic model, but might find solutions in the highest-resolution cosmological simulations, which is beyond the scope of this paper. However, Thompson et al. (2016) show that the cooling can follow the constant mass cooling rate model in a detailed radiatively cooling hot-wind model with mass loading and energy transfer. In their calculation, the stable cooling model is evident in the large mass-loading factor M cool/SFR > 1 case, which is related to another assumption on the boundary condition.

This boundary condition—an infinite ambient hot medium—is required in a steady-state model to balance the cooling rate of the gas. Without this boundary condition, the cooling will reduce the mass and the density of the hot gas, and subsequently reduce the cooling rate in the high-temperature region, which violates the constant mass cooling rate assumption. In Thompson et al. (2016), the low mass-loading factor case shows a flattened dL/d ln T in the high-temperature
region, indicating a lower cooling rate, which directly results from the weakening of the boundary condition. In the context of our gaseous halo model, this boundary condition could be satisfied automatically when the cooling radius is significantly smaller than the virial radius, which means that the gas beyond the cooling radius can be treated as the ambient hot phase gas to supply the cooling medium.

Based on the above discussions, we suggest that gaseous halos should be divided into two categories based on their host galaxy masses. For the low-mass galaxy \((M_h \lesssim 4 \times 10^{11} M_\odot)\), the PIE model is a good assumption, since its halo size is small and the virial temperature is low. For such a gaseous halo, photoionization must be considered, since it provides additional heating to support a more massive gaseous halo, and it changes the distribution of ionization states significantly. Also, low-mass galaxies normally have lower SFR \((\lesssim 1 M_\odot \text{yr}^{-1})\), which reduces the ionizing flux from the host galaxy, and it is approximately correct to assume UVB-dominated photoionization. However, one potential issue is that the stellar feedback is stronger with the decreasing halo mass, which implies that feedback heating is higher and the \(\gamma\) factor is smaller in Equation (2). Considering this effect, the low-mass galaxy may host a higher-mass halo than the PIE model predicts. Considering radiative cooling, we could use the TPIE model, which is more realistic, since the cooling radius is smaller than the virial radius as shown in Figure 7. In the next section, we will show that the photoionization modification in the TCIE model is similar to its effect on the PIE model.

For a high-mass galaxy \((M_h \gtrsim 4 \times 10^{11} M_\odot)\), the virial temperature is high \((>10^{5.5} \text{ K})\) and the cooling radius is smaller than the virial radius. Therefore, we suggest that the entire gaseous halo should be divided into two parts—the inner high-density region within the cooling radius and the outskirts, which is a low-density region. In the inner region, the cooling produces a multiphase medium; therefore, the TCIE model is preferred. Also, in this case, the boundary condition is satisfied to maintain the system in a steady state. Beyond the cooling radius, the PIE model is appropriate due to the density of \(\lesssim 5 \times 10^{-5} \text{ cm}^{-3}\).

### 4.2. The Multiphase Cooling Medium With Photoionization

The TPIE model—the stable radiative cooling model with photoionization—is a more complex extension of the earlier models, and there are two potential issues with such a model. First, with the effect of photoionization increasing, the gas could be in a net heating phase, which could break our assumption of a stable radiatively cooling model. This phenomenon is important where the photoionization might support gaseous components in special situations, such as at \(10^7 \text{ K}\) and within ~1 kpc of the plane (as occurs in the Milky Way—the gaseous disk). However, this case is not the aim of our models. Second, the TPIE model leads to a radial dependence in the temperature distribution, since PIE cooling curves have a dependence on the density. This involves the modeling of the cooling flow, which is not included in our models. Meanwhile, as we will show below, the TCIE and PIE models can be a good approximation for the TPIE model in different situations.

In the TPIE model, there are two modifications compared to the previously defined model. First, the lower limit of temperature in TPIE is no longer fixed at \(10^{4.5} \text{ K}\) due to the potential heating. We set a minimum emissivity of \(10^{-26} \text{ erg cm}^3 \text{ s}^{-1}\) (corresponding to a minimum temperature), which sets a dynamic range of more than three orders of magnitude for the emissivity. If this temperature is higher than \(10^{4.5} \text{ K}\), then the local minimum temperature is changed to the new temperature with the minimum emissivity. In practice, only a few percent of gas has the new lower temperature limit (about \(5 \times 10^4 \text{ K}\) to \(10^4 \text{ K}\), which is not far from our fixed minimum temperature \((3 \times 10^4 \text{ K})\). Second, for different temperatures, the density is also different due to the pressure balance, which leads to different cooling curves. However, this involves radiative transfer to obtain the photon spatial distribution in the gaseous halo. Therefore, we ignore such an effect and use the cooling curve of the total density to calculate the mass–temperature distribution for all of the different temperatures.

In the calculation of TPIE, we use the galaxy sample with the typical SFR dependence on the stellar mass. Other parameters are fixed, including the metallicity of \(Z = 0.3 Z_\odot\), redshift of \(z = 0\), \(\beta = 0.5\), and the impact parameter of 0.3 \(R_{\text{vir}}\). The results are compared to the TCIE and PIE models, shown in Figure 9.

The gaseous halo mass is proportional to the normalization factor in the \(\beta\)-model, which is also indicated by the hydrogen column density. For the gaseous halo mass, the TPIE model converges to the TCIE model for massive galaxies \((\gtrsim 10^{11.5} M_\odot)\), and shows similarities to the PIE model (with the shift to the high-mass galaxy) for low-mass galaxies \((\lesssim 10^{11} M_\odot)\) as expected. Overall, the TPIE is roughly a direct summation of the effect of the photoionization and the cooling temperature distribution. For massive galaxies, the TCIE model is a good approximation of the TPIE model, which has enhanced “low” ionization state ions (e.g., O VII from the cooling of O VIII). In the low-mass range, the gaseous halo is mainly dominated by photoionization, which enriches the high ionization state abundance at low temperatures (e.g., O VI or O VII). Therefore, the TPIE model can be approximated by a combination of PIE and TCIE models for all mass ranges.

### 4.3. The \(\gamma\) Factor

In our model, we introduce a \(\gamma\) factor in Equation (2) to account for the stellar feedback heating. In the previous calculation, this \(\gamma\) factor is fixed at unity for simplicity. However, the \(\gamma\) factor varies over different galaxies, which is determined by the detailed physics of the stellar feedback—supernovae (SNe), stellar winds, photoionization due to starlight, and the radiation pressure (Hopkins et al. 2017). Hopkins et al. (2017) shows that the SN feedback dominates the stellar feedback, although SN feedback alone cannot produce the observations.

SNe can launch a galactic wind that ejects materials and energy into the gaseous halo or beyond the virial radius (Fielding et al. 2017). The strength of the galactic wind can be modeled by the mass-loading factor \(\eta = \dot{M}_{\text{out}} / \dot{M}_{\text{SN}}\). The mass-loading factor (at 0.25 \(R_{\text{vir}}\)) has a dependence on the galactic halo mass (Muratov et al. 2015),

\[
\eta = 2.9(1+z)^{3.3} \left( \frac{V_c}{60 \text{ km s}^{-1}} \right)^{-3.2}, \quad V_c \leq 60 \text{ km s}^{-1},
\]

\[
\eta = 2.9(1+z)^{3.3} \left( \frac{V_c}{60 \text{ km s}^{-1}} \right)^{-1.0}, \quad \text{otherwise},
\]
where $V_c$ is the circular velocity. This is a specific wind model obtained by parametrizing the galactic winds in the FIRE simulations (Hopkins et al. 2014). For the energy carried by the galactic wind, we only consider the kinetic energy and ignore the internal energy, since the temperature of the galactic wind is found to be much lower than the virial temperature in simulations (Fielding et al. 2017). For the wind internal energy, Thompson et al. (2016) showed a semi-analytic model for the cooling wind, and found a temperature drop at the radius of 5–10 kpc for high mass-loading cases ($\eta > 0.8$), which agrees with Muratov et al. (2015). The wind temperature is only about one-tenth of the virial temperature when it enters the innermost radius in our model. Therefore, the internal energy of the wind is negligible compared to the virial temperature of the halo.

The wind velocity is $V_{\text{wind}} = 0.85 V_c^{1.1}$, which is also measured at 0.25 $R_{\text{vir}}$ (Muratov et al. 2015). Based on these relationships, we can set an upper limit for the stellar feedback, since not all of the kinetic energy can be converted into the internal energy of the gaseous halo. Some of the galactic wind will be recycled before it is well-mixed with the gaseous halo, and some will be ejected out of the galaxy halo. Therefore, the lower limit of the $\gamma$ factor is calculated from

$$\frac{1}{\gamma} = 1 + \eta(V_c) \left( \frac{V_{\text{wind}}^2}{V_c^2} - 1 \right).$$

Then, the $\gamma$ factor is around 0.14 for the lowest-mass galaxies and around 0.5 for galaxies with masses higher than $10^{11} M_{\odot}$. We show the halo mass dependence of $\gamma$ in Figure 10.

4.4. The O VI Puzzle

From our models, we find that the O VI column lies in a moderately narrow range close to $10^{14}$ cm$^{-2}$ for all masses of galaxies due to either photoionization (in low-mass galaxies) or a low-temperature cooling medium (in massive galaxies; Figure 11). Current observations show that O VI has a significant dependence on star formation rather than on the stellar mass (Tumlinson et al. 2011), which seems to be reproduced by the TPIE model. Therefore, we compared the prediction from our models with observations, and we adopt three samples—COS-Halos (Werk et al. 2013), Johnson et al. (2015), and Johnson et al. (2017). Our models have the parameters $Z = 0.3 Z_{\odot}$, $\beta = 0.5$, and the SFR is from the main-sequence relationship (also modified using redshift; sSFR $\propto (1+z)^{3}$). The impact parameters of $0.3 R_{\text{vir}}$ and $0.6 R_{\text{vir}}$ are shown since the COS-Halos sample is limited to $<0.55 R_{\text{vir}}$. The redshift is set to 0.2 since most of the O VI samples have $z \approx 0.2$. As shown in Figure 11, the TPIE model can be approximated by the combination of PIE and TCIE with a broad transition around $M_8 \approx 3 \times 10^{11} M_{\odot}$. Therefore, in the following discussion, the TPIE designation represents the combination of the PIE and TCIE models. For low-mass galaxies ($M_8 \lesssim 3 \times 10^{11} M_{\odot}$), O VI is mainly ionized through photoionization for the entire gaseous halo, while for higher-mass galaxies, the cooling medium corresponds to the majority of observed O VI. The TPIE model predicts a narrow range of column densities from $M_8 = 3 \times 10^{10} M_{\odot}$ to $2 \times 10^{11} M_{\odot}$. In most mass regions, the TPIE model predicts an O VI column density of $10^{13.5}$ cm$^{-2}$ to $10^{14.1}$ cm$^{-2}$.
For the COS-Halos sample, the line shape of O VI usually shows multiple components, which can be separated by using Voigt profile fitting. However, in addition to component separation, there is the issue of the host galaxy. Werk et al. (2013) assigned one galaxy for each multicomponent absorption system and calculated the SFR. Therefore, we adopt their measurements based on the apparent optical depth method, which does not separate different components. One caveat is that this treatment of different components might give higher O VI column densities than the isolated gaseous halo. Several galaxies in the COS-Halos sample have other lower-mass galaxies at the same redshift in the same field or lie in galaxy groups, which may introduce contamination from the other galaxies or from the intragroup medium. Since the COS-Halos sample also provides the SFR for each galaxy, we mark in blue a galaxy that has an SFR higher than the SFR calculated from the SFR main sequence, while that with a lower SFR is marked in red. For galaxies with non-detections of O VI, we set the upper limit as the detection limit if it is available.

The Johnson et al. (2015) sample considered galaxies in groups or clusters with isolated galaxies, so we used only isolated galaxies with impact parameters smaller than the virial radius. Johnson et al. (2015) do not have information on the SFR, but they report the galaxy type. Therefore, we assign early-type galaxies to red and late-type galaxies to blue. This color encoding is different from that in the COS-Halos sample, but will not affect the general tendency. The Johnson et al. (2017) sample focuses on dwarf galaxies with stellar masses in log $M_*$ = 7.7–9.2 (Johnson et al. 2017). For these galaxies, no color is assigned, since no SFR information is available.

In Figure 11, most of the detected O VI have column densities of $\gtrsim 10^{14}$ cm$^{-2}$, no matter whether the SFR is above or below the typical SFR. Overall, the difference is about 0.3–0.5 dex, which may be accounted for by two explanations. One is the heating from the stellar feedback, which might produce a smaller $\gamma$ factor in Equation (2). A factor of 4 to 10 can raise the normalization factor in the $\beta$-model by a factor of 2 to 3, which also raises the O VI column density by the same ratio. Similarly, McQuinn & Werk (2018) showed that a cooling flow with 100 $M_\odot$ yr$^{-1}$ can account for the observed O VI column density, and that most of the cooling flow might be destroyed by stellar feedback. However, the galactic-wind-only feedback model is unlikely to be sufficiently energetic based on our calculation in Section 4.3. Another possibility is that the observed O VI is overestimated due to the intragroup medium contamination or the overlap of multiple gaseous halos in the sight line (Stocke et al. 2014).

To address this possibility further, we do not limit the sample to O VI–galaxy pairs, but also consider all intervening O VI absorption systems from blind surveys. We consider three samples—Thom & Chen (2008), Chen & Mulchaey (2009), and Savage et al. (2014). These three samples have some overlap with each other, but since the detection methods are not the same, they are also complementary to each other. In Thom & Chen (2008), the median O VI column density is log $N$(O VI) = 13.9 with a standard deviation of 0.4 dex, while in Chen & Mulchaey (2009), the O VI column density has a median value of log $N$(O VI) = 13.8 and a scatter of 0.4 dex. In Savage et al. (2014), the components are reported separately. The median column density of single O VI components is log $N$(O VI) = 13.68 with a range of 13.00 to 14.59. The average number of components per O VI absorption system is around 1.6, which leads to the average O VI column density for each O VI system of log $N$(O VI) = 13.87. These three surveys are consistent with each other in terms of the median and range of $N$(O VI).

Although these intervening O VI systems currently do not have detected host galaxies, it is possible that they are also the gaseous halo of galaxies, whose luminosities are below 0.1 $L^*$ ($M_h < 3 \times 10^{11} M_\odot$; the detection limit of the COS-Halos galaxy sample). If this is the case, these O VI observations show a significant difference from the COS-Halos sample, whose median is log $N$(O VI) = 14.5 with a scatter of 0.26 dex (only accounting for the detected O VI).
Since the COS-Halos sample provides the SFR for each O\textsc{vi}-galaxy pair, we built a specific model (with $\gamma$) for individual systems based on its stellar mass, SFR, and impact parameter from Werk et al. (2014). We only use the physical impact parameter from the COS-Halos sample, and we recalculate the relative impact parameter using $R_{\text{vir}}$ calculated from Equation (3) with a mean halo density of $200\rho_{\text{crit}}$ rather than $200\rho_{\text{matter}}$. These recalculated virial radii are smaller than those presented in Werk et al. (2014) by a factor of $\approx 30\% - 40\%$ within the redshift range of $z = 0.14 - 0.36$. This modification leads to larger relative impact parameters. For the QSO-galaxy pair J1437+5045 and 317_38 (here we use the same notation in the COS-Halos sample—position angle and angular separation), our calculation leads to the virial radius of 140.2 kpc, which indicates that the absorption system is beyond the virial radius at $z = 0.246$ with the impact parameter of 143 kpc. Although different stellar mass–halo mass relationships and different cosmological constants can lead to different results for the virial radius, the systems with reported $\rho/R_{\text{vir}} > 0.5$ are actually farther out in the halo ($\rho/R_{\text{vir}} > 0.8$).

Our calculations for the O\textsc{vi} column density are shown in Figure 12. If the SFR of a galaxy is the upper limit, we can only derive the upper limit of the O\textsc{vi} column density. Among 30 systems with detectable O\textsc{vi}, there are five that do not have measurable SFRs. It is clear that some of these five systems are in galaxy groups—the galaxy 211_33 of QSO J1133+0327 has a similar redshift ($\Delta z < 0.0002$) to the galaxy 110_5 adopted in the COS-Halos study, and the galaxy 35_14 of QSO J0910+1014 has a similar redshift to the galaxy 242_34. For these O\textsc{vi} absorption systems, it is possible that they are due to the intragroup medium or smaller galaxies that are closer, since we have shown that the O\textsc{vi} column density can be detected for low-mass galaxies ($M_\text{f} < 3 \times 10^{11} M_\odot$), which is consistent with observations (Johnson et al. 2017). Such contamination may also explain some of the differences between the model and the observation. As shown in Bregman et al. (2018), there are two small galaxies surrounding QSO J1009+0713 with a redshift of 0.3556 similar to the galaxy 170_9 (0.3557). For this system, O\textsc{vi} has four components, which have velocities of $-95 \text{ km s}^{-1}$, $25 \text{ km s}^{-1}$, $117.2 \text{ km s}^{-1}$, and $200.7 \text{ km s}^{-1}$. For the galaxy 170_9, our model predicts $\log N(\text{O\textsc{vi}}) = 14.41$, while the two components with high velocities are $14.21 \pm 0.16$ and $14.34 \pm 0.05$, respectively. The two components at low velocities are larger contributors (14.61 $\pm$ 0.05 and 14.52 $\pm$ 0.12) to the total O\textsc{vi} column density of 15.00 $\pm$ 0.03, and we suggest that they may be associated with the two small galaxies with slightly lower redshifts. Overall, our specific models show a difference that is 0.5 dex smaller than the detected O\textsc{vi} from COS-Halos, which is similar to our general comparison shown in Figure 11.

In Figure 12, we also show the relationship between the sSFR and the O\textsc{vi} column density. Our models show results similar to the Evolution and Assembly of Galaxies and their Environments (EAGLE) simulation (Oppenheimer et al. 2016). For star-forming galaxies, the predicted O\textsc{vi} column densities are about 0.5 dex lower than the observation, while we predict lower O\textsc{vi} column densities for passive galaxies (our upper limit is lower than those simulated in EAGLE; Oppenheimer et al. 2016). The difference for passive galaxies may be due to the lack of AGN heating in our models. AGN feedback is also proposed to explain the strong O\textsc{vi} in star-forming galaxies (Oppenheimer et al. 2017), but as discussed above, this difference is possibly due to contamination in the COS-Halos sample.

4.5. The Galactic O \textsc{vii}/O \textsc{viii}

O\textsc{vii} and O\textsc{viii} ions have resonant lines in the X-ray band at 21.60 Å and 18.97 Å. However, the detection of these two ions is limited by the current X-ray observatory sensitivity, and only O\textsc{vii} and O\textsc{viii} in the MW have been confirmed in both absorption and emission (Nicastro et al. 2002; Wang et al. 2005; Henley & Shelton 2012). The modeling of the O\textsc{vii} and O\textsc{viii} emission lines shows that the gaseous halo of the MW has a normalization parameter of $1.35 \pm 0.24 \times 10^{-2} \text{ Z cm}^{-3} \text{ kpc}^{-1.5}$ (Miller & Bregman 2015). For the MW model, we adopt $M_\ast = 7 \times 10^{10} M_\odot$, $M_\text{b} = 1.7 \times 10^{12} M_\odot$, $Z = 0.3 Z_\odot$, and an SFR of $1 M_\odot \text{ yr}^{-1}$. This MW model leads to a normalization parameter of $1.75 \times 10^{-2} \text{ cm}^{-3} \text{ kpc}^{-1.5}$, $1.62 \times 10^{-2} \text{ cm}^{-3}$.
kpc$^{-1.5}$, $1.24 \times 10^{-2}$ cm$^{-3}$ kpc$^{-1.5}$, and $1.15 \times 10^{-2}$ cm$^{-3}$ kpc$^{-1.5}$ for the CIE, PIE, TCIE, and TPIE models, respectively. For a distance to the galactic center of 8 kpc, the sightline with the galactic latitude of 90° has a column density that is half of the sightline with an impact parameter of 0.03 R$_{vir}$ (8 kpc). Then, the predicted column density is $\log N$(O VII) = 15.6, 15.7, 15.8, 15.6 for CIE, PIE, TCIE, and TPIE, respectively. These column densities lead to an EW of 12 mA ($\log N$(O VII) = 15.7), which is less than that in most of the observations, as summarized in Hodges-Kluck et al. (2016), where the mean in this direction ($b \geq 60°$) is about 25 mA. The corresponding O VII column densities are 13.9, 14.7, 13.0, and 14.4 for our four models, which is about one order of magnitude lower than observations (Gupta et al. 2012). These modelings show two issues—the ratio of $N$(O VIII)/$N$(O VII) is too low and the total amount of oxygen is less than the observation.

For the $N$(O VIII)/$N$(O VII) ratio, there are two ways of improving the agreement with Galactic observations—raising the maximum temperature or extending the gaseous halo beyond the virial radius. First, for an $M_h = 1.7 \times 10^{12}$ M$_\odot$ halo, the virial temperature is around $10^6$ K, while the measured hot gas temperature is around $1.5-2 \times 10^6$ K (Henley & Shelton 2012; Miller & Bregman 2015; Nevalainen et al. 2017). Also, it is evident that the hot gas temperature is higher than the virial temperature for most elliptical galaxies (Davis & White 1996; Brown & Bregman 1998; Goulding et al. 2016). This higher temperature can increase the $N$(O VIII)/$N$(O VII) ratio significantly, since the O VIII ion traces the higher-temperature gas. Second, an extended gaseous halo involving photoionization modification also changes this ratio, as shown in Section 3.3. Therefore, increasing the maximum radius helps to increase the $N$(O VIII)/$N$(O VII) ratio.

To increase the total amount of oxygen, there are also two approaches—having an extended gaseous halo and increasing the metallicity. For the MW, the cooling radius is smaller than the virial radius, which means that the larger maximum radius will not reduce the normalization factor in the $\beta$-model, so this modification only increases the gaseous component surrounding the galaxy, hence the metal mass. As stated in Section 3.2, for a given galaxy–gaseous halo pair (fixed SFR and halo mass), higher metallicity leads to a higher total metal mass, although the gaseous halo mass is reduced. Therefore, a higher solar metallicity halo can solve the problem of small O VII column density in our model.

To illustrate these possibilities, we construct a TPIE model to match the galactic O VII and O VIII observations. In the modified model, we vary two parameters—the maximum temperature $T_{max} = \alpha T_{vir}$ and the metallicity. We use the observation summarized in Faerman et al. (2017), which has $N$(O VII) = 1.4 (1.0–2.0) $\times 10^{16}$ cm$^{-2}$ and $N$(O VIII) = 0.36 (0.22–0.57) $\times 10^{16}$ cm$^{-2}$ (also see Gupta et al. 2012; Fang et al. 2015). O VI is also considered to show whether it can be reproduced in the same model, and the column density of the halo O VI is $\log N$(O VI) = 13.95 ± 0.34 (Sembach et al. 2003). For the O VI column density, the contribution from the disk is excluded based on the velocity criterion (Savage et al. 2003).

In Figure 13, we explore the parameter space of $\alpha = 1.5–3$ and $Z = 0.3–1.2 Z_\odot$, which is determined by the $N$(O VIII)/$N$(O VII) ratio and column densities. The acceptable region for each ion is constrained by the observational limits; therefore, the overlap region indicates the preferred parameter space, while the lines crossing indicates the preferred model. Our modified model suggests a supersolar metallicity of 1.02 Z$_\odot$ and a maximum temperature of $1.9 \times 10^6$ K. This high-metallicity solution is not favored since it is very unlikely for the gaseous halo to have a higher metallicity than the galaxy disk. This high metallicity is caused by the high oxygen column density in the observation, which can be solved when the $\gamma$ factor is considered.

Involving the $\gamma$ factor in Equation (2) can lead to a higher mass gaseous halo, since $\gamma < 1$ leads to a higher radiative cooling rate. The typical $\gamma$ factor for the MW is around 0.5. Applying this modification to our model, we will obtain lower-metallicity solutions, since the small $\gamma$ factor leads to a more massive gaseous halo and more metals. Then, it is not necessary to have high metallicities to account for the observed oxygen. We obtain the best model for the MW gaseous halo with the metallicity of 0.55 Z$_\odot$ and the maximum temperature of $1.9 \times 10^6$ K, showing column
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4.6. Intervening Ne VIII/Mg X Systems

Ne VIII and Mg X occurs in the extreme UV band (770 Å and 610 Å, respectively), which can only be detected for extragalactic galaxies due to the wavelength limit of Galactic absorption (912 Å) and due to the UV observing band of HST/COS (1150–1750 Å). Ne VIII is detectable in the redshift of 0.5 to 1.3, while Mg X is detectable between z = 0.9 and 1.8. At higher redshifts, galaxies have a higher mean sSFR, which results in a more massive gaseous halo. In the redshift range of z = 0.7 to z = 1.2, the SFR is raised by a factor of 5–10, which makes the gaseous halo 2–3 times more massive, with a similar increase in the column density of Ne VIII and Mg X. In Figure 14, we show our models of the Ne VIII and Mg X columns at the redshift of 1.

As summarized in Pachat et al. (2017), the median of the detected Ne VIII is log N(NeVIII) = 13.98 ± 0.31, varying in the range of log N(NeVIII) = 13.30 to 14.65. The observed Ne VIII column density shows consistency with our model in a wide galaxy mass range. For the host galaxy, current observations show that it varies from 0.08 L* to ≈2 L* (Narayanan et al. 2012 and reference therein), which is also well-matched with our models. For Mg X, there is only one detection toward LBQS 1435–0134, with the column density of log N(MgX) = 13.89 ± 0.10 (Qu & Bregman 2016), which is also consistent with the model for a (sub-)L* galaxy.

The Mg X system in LBQS 1435–0134 is a good example to study the multiphase medium in the gaseous halo since it has a wide ionization state coverage (i.e., from O III to Mg X), and most of them are high ionization state ions (higher than O IV). In Qu & Bregman (2016), it is modeled by a three-temperature CIE model or a power-law model of the column density–temperature distribution with an index of 1.55. This power-law model has a total χ² of 3.3 with seven degrees of freedom. We notice that the power-law index is approximately the slope of the mass–temperature distribution M(T) in the cooling model, therefore we fit this Mg X system using the TCIE model (Figure 15). The only one variable is the stellar mass, and the SFR is calculated based on the stellar mass and modified by the redshift of 1.2. We use three different impact parameters of 0.2, 0.3, and 0.6. The fitting results are log M* = 10.76 (log M_b = 12.1) with total χ² = 65.7 (doF = 10), 10.64 (12.0) with χ² = 30.0 (10) and 10.56 (11.9) with χ² = 131.1 (10), respectively. Therefore, the Mg X system is likely to be a (sub-)L* galaxy at the redshift of 1.2. For the best model with ρ = 0.3 R_vir, most of the χ² (22.0/30.0) is from three ions, H I, O IV, and Ne VIII. These deviations may be caused by the uncertainty in the lower and the upper limits of the temperature distribution. Extending the lower limit can increase the low and intermediate ionization state ions, while extending the upper limit can decrease the Ne VIII column density as shown in Figure 14 with regard to log M_b = 12.0. Therefore, although the best reduced-χ² is around 3, it is a valuable step in modeling such a complex object (the gaseous halo) with a simple physical model.
4.7. Mass Budget

The galaxy’s missing baryon problem is a crucial aspect of both observation and theory for galaxy formation and evolution, so we also check whether our gaseous halo model can address this issue. In Figure 16, we show the baryonic fraction for models considered for typical star-forming galaxies. In all mass regions, the cosmic baryonic fraction is significantly higher than the total baryonic fraction of galaxies, which indicates that the gaseous halo within the virial radius cannot account for the missing baryons of galaxies in the mass region considered. The overall tendency shows that the low-mass galaxy is more baryon-poor than the massive galaxy, showing a sharp rise between $M_h \sim 10^{11} M_\odot$ and $4 \times 10^{11} M_\odot$. The baryonic fraction is almost a constant $f_b \approx 0.05-0.06$ for galaxies with masses higher than $5 \times 10^{11} M_\odot$.

These baryonic fractions are the median values for galaxies at different masses, while it is possible to have a significant scatter due to the SFR scatter. With the SFR scatter of 0.4 dex (Renzini & Peng 2015), the baryonic fraction could have a scatter of 0.2 dex based on the square root relationship between the sSFR and the gaseous halo mass. This scatter is consistent with cosmological simulations, which shows the baryonic fraction can vary between 20% and 100% of the cosmic baryonic fraction (Marinacci et al. 2014; Muratov et al. 2015; Schaller et al. 2015; Suresh et al. 2017).

That low-mass galaxies have a low $f_b$ is the direct result of both low stellar mass and high cooling rate. Although they have a relatively high sSFR, the gaseous halo is still low mass and comparable to the stellar mass within a factor of 2. This tendency is consistent with the simulation effort (EAGLE) when the halo mass is smaller than $3 \times 10^{12} M_\odot$ (Schaller et al. 2015; Schaye et al. 2015). EAGLE has prescriptions for the star formation, stellar evolution, stellar feedback, and AGN feedback. The discrepancy between the EAGLE simulations and our models in the high-mass region is due to the lack of heating from the AGN feedback in our model, which is positively related to the halo mass rather than the stellar mass. In the low-mass region, the baryonic fraction in our model is slightly less than that of Schaller et al. (2015) by a factor of $\approx 2$ at the halo mass of $10^{11} M_\odot$. This might emphasize the importance of stellar feedback for low-mass galaxies, and a $\gamma$ factor of 0.1–0.2 can account for such a difference. Involving the $\gamma$ factor described in Section 4.3, we set the upper limits for the baryonic fraction in our models, which is also shown in Figure 16. The modification on the $\gamma$ factor leads to a higher baryonic fraction in low-mass galaxies, which is consistent with our hypothesis that low-mass galaxies have higher stellar feedback heating.

However, the trend of increasing baryonic fraction with halo mass is significantly different from that in the Illustris simulation, which also has full stellar physics and AGN feedback (Vogelsberger et al. 2014). The Illustris simulation shows the opposite tendency, with the low-mass galaxy having more baryonic material (even higher than the cosmic baryonic fraction) enclosed in the virial radius (Suresh et al. 2017). This may be a result of photoionization, which is included in Illustris but not in EAGLE. Our models show that the photoionization modification is important for low-mass galaxies, since it can support a more massive gaseous halo. Nevertheless, the divergence between Illustris and EAGLE is very unlikely to be caused by the photoionization modification, since it has also been shown that photoionization can only raise the gaseous halo mass by a factor of about 2, down to the stellar mass of $8 \times 10^7 M_\odot$ (see Section 3.1). This difference is more likely to be caused by the weak stellar feedback employed in Illustris, which is set to keep gas inside the halo (Suresh et al. 2017).

Another consideration that might moderate the missing baryon problem is having a gaseous halo extending beyond the virial radius. When we change the outermost radius for the gaseous halo from one virial radius to twice the virial radius, the gaseous halo mass is increased by a factor of 2–3. For an $L^*$ galaxy ($M_h = 1.7 \times 10^{12} M_\odot$, SFR = $5 M_\odot$ yr$^{-1}$), the cooling radius is 173 kpc (less than the virial radius of 253 kpc), which indicates that the increase of the outermost radius will not change the normalization factor in the $\beta$-model. Modifying the outermost radius raises the mass from $2.6 \times 10^{10} M_\odot$ to $7.4 \times 10^{10} M_\odot$, raising the baryon fraction from 0.055 to 0.083. Therefore, in the case where the cooling radius is smaller than the virial radius, the factor is fixed at 2.83; otherwise, the factor is slightly smaller but still around 2. This would raise the baryonic fraction, but is still not enough to account for all of the missing baryons for $L^*$ galaxies. For the
high-mass and the low-mass end of the galaxy distribution, the total baryonic fraction is raised by a factor of $\approx 2$, since most of the mass is in the gaseous halo rather than in the stellar content.

### 4.8. Future Observations

An issue highlighted by this work is that one needs measurements for ions that are the dominant volume-filling ions, which trace the gas that is near hydrostatic equilibrium and are at the temperature of most of the gaseous mass. In practice, this requires that we obtain O VII and O VIII absorption line data for galaxies with $M_h > 3 \times 10^{11} M_{\odot}$. Absorption in O VII is available for the MW for about two dozen sight lines and in O VIII for a handful of objects (Fang et al. 2015; Hodges-Kluck et al. 2016). A significant advance can be realized through improved S/N for O VII and especially O VIII as well as for a larger number of sight lines. This will not happen with existing instruments (XMM-Newton and Chandra), which have already devoted about 20 Msec of observing time toward bright objects, so improvements would require several times this amount.

For external galaxies, no O VII or O VIII absorption lines have been detected (Nicastro et al. 2016b). Sight lines through the halos of external galaxies ($0.3 \sim R_{200}$) are expected to be nearly an order of magnitude weaker than those from the MW. The failure to see these lines is consistent with model predictions, given the sensitivity of current instruments and the amount of redshift space that has been probed.

Detecting O VII and O VIII through a sample of external galaxy halos will require a new instrument with capabilities that offer at least an order of magnitude improvement. Such an instrument would also offer a breakthrough in the study of these lines in the MW. This level of improvement is possible through Arcus (Smith et al. 2016), an Explorer-class mission that will have nearly an order of magnitude improvement in both spectral resolution and in collecting area relative to the XMM-Newton/RGS (and a larger improvement relative to the Chandra/LETG). The spectral resolution will be about 3000 ($100 \text{ km s}^{-1}$), providing kinematic information as well as insights into turbulence. The Athena mission will also add to our understanding of these absorption systems, but its spectral resolution is poorer than that of XMM-Newton ($1300 \text{ km s}^{-1}$), so kinematic information will be limited (Barcons et al. 2017).

The Lynx mission concept will offer another order of magnitude increase in collecting area, relative to Arcus and with double the resolution ($50 \text{ km s}^{-1}$), which approaches the thermal width of gas at $2 \times 10^6 \text{ K}$ (Gaskin et al. 2016). It will be sensitive to much weaker lines and will provide excellent kinematic information.

### 5. Summary

We report on a gaseous halo model connecting the SFR and the radiative cooling rate, including photoionization and a multiphase medium. This model predicts a gaseous halo mass comparable to the stellar mass, and can be employed to understand observations of high ionization state ions (i.e., O VI, O VII, Ne VIII, Mg X, and O VIII). We summarize our major results as follows:

1. Photoionization is the most important physical process in determining the relative ion distribution in the entire extended gaseous halo of low-mass galaxies and the outskirts of massive galaxies. For low-mass galaxies ($M_h < 3 \times 10^{11} M_{\odot}$), photoionization supports a more massive gaseous halo and generates high ionization state ions (e.g., O VI and O VII). For more massive galaxies, photoionization leads to more high ionization state ions in the outskirts (i.e., the O VIII of the MW).

2. The multiphase medium within the cooling radius can be modeled by the distribution $M(T) \propto T^2$. This multiphase medium leads to a flattened dependence of the high ionization state ion column densities with galaxy halo mass. More relatively low ionization state ions (compared to the virial temperature) are generated because of the cooling from the high-temperature medium.

3. Overall, our models predict that the mass of the gaseous halo is comparable to the stellar mass (within one order of magnitude) for star-forming galaxies over all halo masses. The cooling radius is expected to vary between 50 and 200 kpc, which is a small variation when compared to the two order of magnitude range in halo mass.

4. O VI has a narrow range ($\log N$(O VI) = 13.5–14.3) for galaxies with $M_h < 10^{11} M_{\odot}$. Above $M_h = 3 \times 10^{11} M_{\odot}$, O VI is mainly from collisional ionization, while below this mass, photons from the UVB ionizes most of the O VI ions. The predicted O VI column density range is consistent with blind O VI surveys.

5. A modified model is constructed for the Galactic O VII and O VIII, with changes in the standard metallicity of 0.55 $Z_{\odot}$ and a maximum temperature of $1.93 \times 10^6 \text{ K}$, which is above the virial temperature but similar to that derived from emission ratios. Such a gaseous halo leads to a hot halo mass of $1.9 \times 10^{10} M_{\odot}$ within the virial radius, which contributes to 7% of the total baryonic mass of the MW.

6. For intervening Ne VIII and Mg X at $z = 0.5–1.3$, our models predict column densities of $\approx 10^{14} \text{ cm}^{-2}$, which is consistent with observations and informs the detection limit for future observations.

7. Such a gaseous halo cannot close the census of the galaxy’s missing baryons within $R_{200}$. Where it is possible to compare, our model results are similar to those of the EAGLE simulations, and about the half of the baryons are still missing for $L^*$ galaxies within the virial radius.

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