Exploring the Physical Properties of the Cool Circumgalactic Medium with a Semi-Analytic Model

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ABSTRACT

We develop a semi-analytic model to explore the physical properties of cool pressure-confined circumgalactic clouds with mass ranging from 10 to 10$^8$ M$_\odot$ in a hot diffuse halo. We consider physical effects that control the motion and mass loss of the clouds, and estimate the lifetime and the observed properties of individual cool gas clouds inferred from the CLOUDY simulation. We model the ensemble properties of the cool CGM with clouds originated from outflows, inflows, or/and in-situ formation with a range of initial cloud mass function and velocity distribution. Our results show that the cool pressure-confined gas clouds have physical properties consistent with absorption line systems with neutral hydrogen column densities N$_{\text{HI}} \geq 10^{18.5}$ cm$^{-2}$ and with sizes about 10-100 pc, such as strong metal absorbers, sub-DLAs, and DLAs. The cool circumgalactic clouds are transient due to evaporation and recycling and therefore a constant replenishment is needed to maintain the cool CGM. We find that an outflow model can broadly reproduce three cool gas properties around star-forming galaxies simultaneously: the spatial distribution, down-the-barrel outflow absorption, and gas velocity dispersion. Both a constant in-situ model and gas inflow model can reproduce the observed covering fractions of high N$_{\text{HI}}$ gas around passive galaxies but they fail to reproduce sufficient number of low N$_{\text{HI}}$ systems. The limitations and the failures of the current models are discussed. Our results illustrate that semi-analytic modeling is a promising tool to understand the physics of the cool CGM which is usually unresolved by state-of-the-art cosmological hydrodynamic simulations.

Keywords: quasars: absorption lines, galaxies: halos, intergalactic medium

1. INTRODUCTION

Gas around galaxies, the cirumgalactic medium (CGM, Tumlinson et al. 2017, for a review), plays a key role in understanding galaxy formation and evolution. As the interface between galaxies and the intergalactic medium (IGM), CGM contains signatures of gas flow processes that drive the evolution of galaxies. Since the first discovery of the CGM (Bergeron 1986), studies have revealed the complex nature of the CGM. The CGM is multi-phase, consisting of gas with a wide-range of temperature, from the virial temperature of the halos $\sim 10^6$ K to $\sim 10^9$ K, and wide range of density, from $10^{-4}$ to $10^{-3}$ cm$^{-3}$. In addition, the properties of galaxies and their CGM have complicated relationships; while cool gas ($\sim 10^4$ K) appears to exist around both star-forming and passive galaxies (e.g., Chen et al. 2010; Thom et al. 2012; Lan et al. 2014), warm gas ($\sim 10^5$ K) is much more abundant around star-forming galaxies than around passive galaxies (e.g., Tumlinson et al. 2011).

To interpret these observational results, simulations and theories for the CGM have been developed. Recently, many studies have attempted to address the origin of the excess of warm gas traced by OVI absorption lines (diffuse gas with $\sim 10^5$ K) around star-forming galaxies (e.g., Oppenheimer et al. 2016; Werk et al. 2016; Suresh et al. 2017; Bordoloi et al. 2017; Faerman et al. 2017; Mathews & Prochaska 2017; Guchi et al. 2017; Nelson et al. 2018; McQuinn & Werk 2018; Oppenheimer et al. 2018; Roca-Fàbrega et al. 2018; Stern et al. 2018). On the other hand, although cool gas has been observed ubiquitously around galaxies (as, e.g., traced by MgII absorption lines), only limited attempts have been made to model and understand the origin of the cool halo gas (e.g., Mo & Miralda-Escude 1996; Maller & Bullock 2004; Kaufmann et al. 2009; Bordoloi et al. 2014; Ford et al. 2014; Faucher-Giguère et al. 2016; Oppenheimer et al. 2018b; van de Voort et al. 2018). More importantly, observations (e.g., Rauch et al. 1999; Rigby et al. 2002; Prochaska & Hennawi 2009; Lan & Fukugita 2017) and simulations (e.g., McCourt et al. 2018; Liang & Remming 2018; Sparre et al. 2018) have shown that the physical scale relevant to the cool circumgalactic gas is of the order of a few tens of parsec or even smaller, which is several orders of magnitude smaller than the resolution of any current galaxy hydrodynamic simulations (see Figure 9 in Sparre et al. 2018). This discrepancy poses a challenge to understanding the physics for the CGM and galaxy formation.
To overcome the limitation of numerical resolution, we develop a semi-analytic model for the cool circumgalactic gas, motivated by earlier analytic works. We revisit the idea of cool gas clouds being in pressure equilibrium with an ambient hot halo gas (Mo & Miralda-Escude 1996; Maller & Bullock 2004) and estimate their lifetime, motion, and trajectory by taking into account the effects of gravity, ram pressure and heat evaporation. We then model the ensemble properties of the cool gas clouds in halos considering scenarios of outflows, inflows, and in-situ formation, identifying key mechanisms that govern the properties of cool CGM. With this flexible model, we explore how physical mechanisms affect observational signatures of the CGM.

This paper is organized as follows. In Section 2, we describe the physical effects that can affect the cool gas clouds that we consider. In Section 3, we summarize the evolution of individual clouds and present the ensemble properties of cool gas and their evolution. We discuss other implications in Section 4 and summarize our results in Section 5. Throughout the paper we adopt a flat ΛCDM cosmology with $h = 0.7$ and $\Omega_M = 0.3$.

2. MODEL SETUP

To explore the properties of cool pressure-confined clouds in the CGM, we first introduce the model components that control the motion and the lifetime of individual clouds (§2.1). We then describe our outflow and inflow models to populate an ensemble of clouds into the CGM and to characterize the statistical properties of the cool clouds (§2.2).

2.1. Model components for individual clouds

Figure 1. Hot gas density and temperature profiles.

Figure 2. Cloud properties as a function of position. Top: $10^4$ K cool gas volume density. Middle: neutral hydrogen (solid color lines) and total hydrogen (dashed color lines) column densities as a function of cloud mass. The difference is due to the ionization by extragalactic background radiation field. The data points show the neutral hydrogen column densities traced by strong MgII absorbers from observations. Note that data points are in the projected distance. Bottom: cloud radius as a function of mass.

Basic properties- The evolution of cool clouds is modeled under the influence of a dark matter halo and a hot diffuse gas halo. As an demonstration, we adopt a $10^{12} M_\odot$ dark matter halo with a NFW profile (Navarro et al. 1996) and concentration $c = 10$. For the hot
gaseous halo, we use the gas profile derived by Maller & Bullock (2004), assuming that the initial hot gas had cooled over 6 billion years and the residual hot gas had reached hydrostatic equilibrium adiabatically at $z = 0.5$. The metallicity of the hot gas is assumed to be 0.1 solar. Figure 1 shows the adopted hot gas density (left axis) and the temperature (right axis) profiles.

The physical properties of cool gas clouds are obtained by assuming that cool gas clouds are in pressure equilibrium with the surrounding hot gas halo (e.g. Mo & Miralda-Escude 1996),

$$n_{\text{cloud}} T_{\text{cloud}} = n_{\text{hot}} T_{\text{hot}}.$$  

This is motivated by the fact that a gas cloud can establish pressure equilibrium with its surrounding typically within the sound crossing time. For a cloud with $10^4 \, M_\odot$, $n \sim 0.1 \, \text{cm}^{-3}$, and $T \sim 10^4 \, K$, the sound crossing time is about 10 Myr, much shorter than the survival time of the clouds, which is greater than 100 Myr. We assume that the temperature of gas clouds is $10^4 \, K$ with spherical geometry. The physical properties of a cool gas cloud of a given mass $M_{\text{cloud}}$, such as its size $r_{\text{cloud}}$, volume density $n_{\text{cloud}}$, the total hydrogen column density $N_{\text{HI}}$, neutral hydrogen column density $N_{\text{HI}}$, and ionization fraction, are then obtained self-consistently by using CLOUDY simulation (Ferland et al. 2013). Gas clouds are assumed to be photo-ionized by an extra-galactic radiation field described by the model of Haardt & Madau (2001).

In Figure 2, we show the properties of cool clouds as functions of cloud mass and location in the halo. The top panel shows the volume densities of the cool gas clouds. In the middle panel, the solid color lines show the neutral hydrogen column densities $N_{\text{HI}}$ of clouds and the dashed lines show the total hydrogen column densities. The neutral hydrogen column densities fall within the range between $10^{18}$ and $10^{20.5} \, \text{cm}^{-2}$, similar to that observed in sub-damped Lyman systems (strong Lyman-limited systems) and damped Lyman systems. For comparison, the grey squares show the neutral hydrogen column densities traced by strong MgII absorbers, obtained by using MgII galaxy-absorber pairs from Nielsen et al. (2013) and the empirical relationship between MgII rest equivalent width and neutral hydrogen column density from Lan & Fukugita (2017):

$$N_{\text{HI}} \simeq 10^{19} \left( \frac{W_{2796}}{1 \text{Å}} \right)^{1.7} (1 + z)^{1.9} \, \text{cm}^{-2}.$$  

Note, however, that the grey data points use the projected distance instead of the three-dimensional distance in the halo.

At small scales, the neutral hydrogen column density depends on the volume density of clouds:

$$N_{\text{HI}} \propto n_{\text{HI}} \propto n_{\text{cloud}}^{2/3} M_{\text{cloud}}^{1/3}. \quad (3)$$

However, beyond a certain distance scale, the neutral hydrogen column densities drop rapidly due to that the volume density of the cloud is too low to be self-shielded from the ionization radiation field. This scale depends on the cloud mass, as shown in the figure. In the bottom panel of Figure 2, we show cloud radius (assuming spherical shape) as a function of mass and distance. The cloud radius ranges from 10 pc to a few hundred pc, with a typical value of ~ 100 pc for cloud mass ~ $10^4 \, M_\odot$.

**Motion and survival** - To model the motion and survival of the cool clouds in the halo, we consider the following effects:

- **Motions of clouds** - the motion of a cloud is governed by the gravitational potential provided by the dark matter halo and the ram pressure of the hot gas halo:

$$\frac{d^2 r}{dt^2} = -\frac{GM_{\text{DM}}(<r)}{r^2} + \frac{1}{2} C_d P_{\text{ram}}(r) \frac{n_{\text{cloud}}(r)}{M_{\text{cloud}}} \left[ \frac{\pi r_{\text{cloud}}^2}{M_{\text{cloud}}} \right].$$

where $v_{\text{cloud}}$ is the velocity of the cloud and $C_d$ is the coefficient for ram pressure. By default, we set $C_d$ to be 1 but we will explore the possibility with lower coefficient in Section 3.3.1. The ram pressure scales with the mass of clouds as

$$P_{\text{ram}} \propto n_{\text{cloud}}^{-2/3} M_{\text{cloud}}^{-1/3} \propto N_{\text{HI}}^{-1}. \quad (5)$$

Thus, massive clouds experience less ram pressure effect comparing with small clouds. In this paper, we only consider radial motion of the clouds.

- **Cloud disruptions** - there are several mechanisms that could affect the mass of a cloud. Mo & Miralda-Escude (1996) (see also Maller & Bullock (2004)) provides a detail summary about the possible mechanisms. Here we briefly discuss the key mechanisms:

  (1) **Self-gravity** - The upper limit of a cloud mass in our analysis is constrained by the Jeans mass (Jeans 1902) above which the cloud collapses due to its self-gravity. The Jeans mass of clouds in our model setup is about $10^8 M_\odot$.

  (2) **Hydrodynamic instability** - When a dense cloud moves through a hot gas halo, the cloud is subject to the hydrodynamic instability, such as Kelvin-Helmholtz instability and Rayleigh-Taylor instability. The characteristic timescale of the instabilities (e.g. Murray et al. 1993) are

$$t_{\text{instability}} \sim \frac{r_{\text{cloud}}}{v_{\text{cloud}}} \left[ \frac{T_{\text{Hot}}}{T_{\text{cloud}}} \right]. \quad (6)$$

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1 We use the unpublished updated 2005 version implemented in the CLOUDY simulation.
Based on the characteristic timescale, a cool gas cloud can only travel a distance that is about 10 times its radius (assuming $T_{\text{Hot}} \sim 100 T_{\text{cloud}}$) before it is destroyed by the instability. However, several studies have shown that other mechanisms can suppress the effects of hydrodynamical instabilities, such as radiative cooling (Vietri et al. 1997), magnetic fields (e.g., Malagoli et al. 1996; McCourt et al. 2015), and the presence of heat conduction layers (Armillotta et al. 2017), and mixing layer between cool and hot gas (Gronke & Oh 2018). Motivated by these studies, we assume that the clouds are intact under the effect of the hydrodynamic instability.

**3) Heat evaporation** - Surrounded by hot ambient gas, cool gas clouds are subject to mass loss due to the heating by the hot gas. The classic mass loss rate due to the evaporation is derived by Cowie & McKee (1977):

$$M_{\text{cloud,classic}} = \frac{dM_{\text{cloud}}}{dt} = 2.75 \times 10^4 T_{\text{hot}}^{5/2} r_{\text{cloud}} \left(\frac{30}{\ln \Lambda}\right) \text{g s}^{-1}$$

where $\ln \Lambda$ is the Coulomb logarithm with value about 30. Dalton & Balbus (1993) generalize the mass loss rate including the case when the heat conduction is saturated:

$$M_{\text{cloud}} = f w M_{\text{cloud,classic}},$$

where $w$ is the modified factor depending on the saturation parameter,

$$\sigma_0 = \frac{2\kappa_{\text{hot}} T_{\text{hot}}}{25 \Phi_{\text{hot}} c_{\text{hot}}^3 r_{\text{cloud}}}$$

with $\kappa_{\text{hot}} = 1.84 \times 10^{-5} T_{\text{hot}}^{5/2} (\ln \Lambda)^{-1} \text{[cgs]}$. If $\sigma_0 > 1$, the saturation will reduce the mass loss rate to $w M_{\text{cloud,classic}}$. If $0.027 < \sigma_0 < 1$, the cloud undergoes classical evaporation. Finally, we introduce a suppression factor $f$ for the evaporation rate in Eq. 7. We adopt $f = 0.05$ to account for the effect of other mechanisms such as magnetic field (e.g., Chandran & Cowley 1998) on the efficient of mass evaporation. We note that some studies have constrained the $f$ value to be about 0.01 or lower (e.g., Binney & Cowie 1981; Nipoti & Binney 2004). We discuss the effect of $f$ value in Section 4.

2.2. Model components for an ensemble of clouds

To populate an ensemble of clouds in the halo, we consider three cases: (i) clouds originated from outflows, i.e. gas ejected from the center of halo; (ii) clouds originated from inflows, i.e. gas freely falling from the virial radius of the halo; (iii) gas clouds formed in-situ in the halo. This framework enables us to investigate how the statistical properties of cool clouds, such as their spatial distribution, depend on the origin of the clouds. The model components are summarized below:

- **Origins of cool gas clouds** - we consider cool gas clouds have three origins: (1) outflow gas clouds ejected at 1 kpc from the center of the halo, (2) inflow gas from the virial radius of the halo, and (3) in-situ gas formed in the halo with distribution following NFW and power law profiles.

- **Gas flow mass rate** - we consider a burst gas flow and a constant gas flow for the outflow models. Mass outflow rate for the burst model follows an exponential form similar to the star-formation history of galaxies (e.g. Bruzual & Charlot 2003):

$$\frac{dM_{\text{outflow}}}{dt} = 340 e^{-t/200} M_\odot / \text{yr}. \quad (10)$$

For the constant outflow and inflow models, we assume a constant gas flow with $20 M_\odot \text{yr}^{-1}$. These models eject $8 \times 10^{10} M_\odot$ in total over 4000 Myr, and the value is chosen to produce the cool CGM mass of about $10^{10} M_\odot$, similar to that observed. We note that there is a degeneracy between the gas flow rate and the evaporation suppression factor $f$ for the evaporation, as discussed in Section 4.

- **Initial cloud mass function** - to populate the total gas mass into clouds, we introduce an initial cloud mass function to account for possibly coverage of cloud masses. We assume that (i) the mass spectrum of cool gas clouds follows a power law distribution with a power $\alpha$: 

$$N(M_{\text{cloud}}) \propto M_{\text{cloud}}^\alpha, \quad (11)$$

(ii) the mass spectrum follows a Schechter function with a power $\alpha$ and a characteristic cloud mass $M_*$:

$$N(M_{\text{cloud}}) \propto M_{\text{cloud}}^\alpha \times e^{-M_{\text{cloud}}/M_*}. \quad (12)$$

In addition, we put limits on the initial maximum and minimum cloud masses. The maximum cloud mass is $10^8 M_\odot$ above which the clouds collapse due to self-gravity. The minimum cloud is set to be $10^2 M_\odot$. The initial cloud mass function plays an important role in the structure of the circum-galactic medium. The value of $\alpha$ determines how the total cloud mass is distributed in cloud mass.
Figure 3. Examples of trajectories of clouds with initial velocity of 500 km/s (escaping velocity) and initial mass from $10^2$ to $10^7 M_\odot$. Half filled cycles (empty cycles) indicate the times when clouds lose half (all) of their initial mass due to evaporation. The dashed line shows the trajectory without the effect of hot gas. The hot gas prevents the escape of clouds with ram pressure and destroys the small cool clouds with evaporation.

and, therefore, the column density $N_{\text{HI}}$ distribution in the CGM and the covering fraction of gas clouds around galaxies. With a fixed total cloud mass, the covering fraction depends on the cloud mass as

$$f_c \propto N_{\text{cloud}} \times \Sigma_{\text{cloud}} \propto M_{\text{cloud}}^{-1/3},$$

where $\Sigma_{\text{cloud}}$ is the cross section of a cloud. We will pay special attention to how the properties of the CGM depend on $\alpha$.

- **Velocity distribution** - we assume that the velocity distribution of outflow clouds follows a normal distribution with mean velocity equal to 300, 500, or 700 km/s, and a width of 200 km/s. These numbers are motivated by observations (e.g. Rubin et al. 2014) and theoretical models (e.g. Murray et al. 2011). Clouds are assumed to be ejected from the center isotropically.

3. RESULTS

3.1. **Evolution of individual clouds**

We first study the motion and mass evolution of clouds derived from Equations (4) and (8). Figure 3 shows examples of the trajectories of clouds with masses from $10^2$ (blue line) to $10^7 M_\odot$ (red line), and with initial velocity $V_{\text{init}} = 500$ km/s ejected at 1 kpc from the center of the halo. Ballistic motion without the effect of ram pressure is shown with the black dashed line. The half-filled and open circles indicate the times when the cloud has lost half of its initial mass and is totally evaporated, respectively. As shown in the figure, the effect of ram pressure depends on the mass of clouds: massive clouds are able to travel beyond 100 kpc while small clouds are stopped by ram pressure and fall back within 50 kpc. Without ram pressure, clouds with the same initial velocity should all follow the ballistic motion. For cloud masses $< 10^4 M_\odot$, no clouds can escape the halo even if the initial velocity is comparable to the escape velocity of the gravitational potential. In addition to ram pressure, the hot ambient gas can also remove gas from clouds via heat evaporation. Clouds with masses less than $10^4 M_\odot$ lose all the mass within a few hundred Myr due to evaporation, while clouds with masses greater than $10^4 M_\odot$ fall back to the center with a fraction of their initial masses. The estimated evaporation timescales for clouds are similar to the timescale estimation from hydrodynamical simulations by Armillotta et al. (2017) for individual clouds.

We summarize the fates of clouds with various initial velocities and masses ejected at 1 kpc from the halo center in Figure 4. The left panel shows the maximum distance that a cloud can travel and the right panel shows...
Figure 4. Summary of the fates of outflowing clouds with various initial masses and velocities. Left: maximum distance. Right: survival time.

Figure 5. Summary of the fates and survival time of inflow clouds with various initial masses and positions.

the survival time of the clouds. The fates of clouds can be classified into three categories:

1. Evaporation (left): Clouds with relative low masses and high velocities lose all their masses due to evaporation within 50-1000 Myr while traveling in the halo. Even with extreme initial velocities, small clouds can only reach about 50-100 kpc from the center before being evaporated.

2. Survival (top right): Clouds with high masses and high velocities can survive over 4 Gyr and most of them can escape the halo.

3. Recycling (bottom right): Clouds with high masses but low velocities eventually fall back to the halo center with a fraction of their initial masses. The timescale for clouds to be recycled is about 500-1000 Myr depending on the initial velocity consistent with results from hydrodynamical simulations (e.g., Ford et al. 2014; Anglés-Alcázar et al. 2017).

In addition to clouds ejected from the halo center, we also model the gas clouds freely falling from a given initial position towards the halo center. The fates of the inflowing gas clouds are summarized in Figure 5 showing the survival time of the clouds. Similarly to the outflow case, clouds with low masses are evaporated in the circumgalactic space while massive clouds can reach the halo center with a fraction of their initial masses. For free falling clouds from the halo virial radius (~200 kpc), it takes about 2 Gyr to reach the center.

3.2. Mass Evolution

With the properties and fates of individual clouds modeled, we can now explore how the ensemble of clouds evolves with time. To do so, we eject clouds with a given flow rate and a given initial cloud mass function, as discussed in Section 2.2. We estimate the fractions of initial ejected mass (1) staying in the circumgalactic space, (2) moving beyond the virial radius, (3) evaporated, and (4) falling back into the center, and explore how the different fractions change with model parameters. Figure 6 shows the results for three modes of gas flow models: the burst outflow model (left column), constant outflow (middle column), and constant inflow models (right column). We also explore three initial mass functions, power laws with $\alpha = 0$ (top panel) and $\alpha = -1$ (mid-
Figure 6. Mass evolution of ejected clouds with three gas flow modes. Left: Burst outflow models; Middle: constant outflow models; Right: constant inflow models. The total ejected mass is shown with the black lines. The masses in the circumgalactic space and moving beyond the virial radius are shown in blue and purple, respectively. The mass that recycles back to the center is shown in green and that gets evaporated is shown in red.

Let us first focus on the burst outflow model with $\alpha = 0$, shown in top-left panel, in which all the mass ($8 \times 10^{10} M_\odot$) is ejected in 500 Myr. The mass in the circumgalactic medium reaches its maximum at around 400 Myr, and declines afterwards. After 1 Gyr, $\sim 40\%$ of the total mass has moved beyond the virial radius and a similar fraction of the mass recycled back to the center. Only a small fraction of mass remains in the halo (15\%) or gets evaporated (5\%). This demonstrates that a single burst event cannot sustain the circumgalactic medium for a timescale of billion years. In contrast, in the constant outflow model, shown in the top middle panel, the mass in the circumgalactic region can reach $\sim 10^{10} M_\odot$ and remains more or less constant. This is clearly due to the balance between the constant mass outflow, the recycled mass, and the escaped mass. As in the burst outflow, $\sim 40\%$ of the ejected mass returns to the center as recycled mass, while $\sim 40\%$ escapes the halo. The mass evolution of the constant inflow model behaves similarly to the constant outflow model except...
that it takes about 2000 Myr for the inflowing clouds to reach the halo center.

The mass evolution also depends on the shape of the initial mass function: the typical cloud mass decreases and the evaporation timescale becomes shorter as $\alpha$ decreases. By changing the shape of the initial mass function from $\alpha = 0$ to $\alpha = -1$, the amount of evaporated mass increases by a factor of 10, as shown in the middle panels of Figure 6. Finally, adopting a Schechter function with $\alpha = -1$ and $M_\alpha = 10^{6.5} M_\odot$ as the initial cloud mass function further reduces the number of massive clouds and enhances the mass fraction of evaporation to about 80%, as shown in the bottom panels of Figure 6. One interesting implication is that heat evaporation can reduce the total cloud mass from outflows. Therefore, the outflow mass estimated from the cool CGM mass is only a lower limit (e.g., Lan & Mo 2018) and it can be an order of magnitude lower than the intrinsic outflow mass depending on the shape of the mass function. Similarly, the evaporation reduces the total infalling cloud mass that reaches the center. This might be a possible mechanism to prevent further star-formation in passive galaxies (see also Zahedy et al. 2018). These results demonstrate that the total mass in the CGM depends on the shape of the initial cloud mass function. In the following, we will show that the shape of the initial mass function also plays an important role in determining the profile of the circumgalactic medium.

3.3. **Spatial distribution of cool gas clouds**

We now investigate the spatial distribution of the pressure-confined gas clouds as a function of different initial mass function and initial velocity. To guide the exploration, we compare our modeled gas properties with the observed neutral hydrogen gas around star-forming and passive galaxies at redshift 0.5. To this end, we use the distribution of the neutral hydrogen traced by strong MgII absorbers. Such absorbers, with $W_{\lambda 2796} > 0.4$ Å, have been considered as a tracer of the cool circumgalactic gas with neutral hydrogen column densities $N_{\text{HI}} > 10^{18.5}$ cm$^{-2}$ and volume densities $n_H \sim 0.3$ cm$^{-3}$ (e.g., Rao et al. 2006; Ménard & Chelouche 2009; Lan & Fukugita 2017), consistent with the properties of the pressure-confined cool clouds in our model. Strong MgII absorbers have been observed around both star-forming and passive galaxies, and their distributions around both types of galaxies are similar on large scales ($r_p > 50$ kpc) (e.g., Chen et al. 2010; Nielsen et al. 2013; Lan et al. 2014; Lan & Mo 2018). Within 50 kpc, however, there is more MgII absorption around star-forming galaxies than around passive galaxies. This excess absorption is most likely associated with outflows, as is inferred from the azimuthal angle distribution (e.g., Bordoloi et al. 2011; Lan & Mo 2018). In our analysis, we use the MgII covering fraction at redshift 0.5 around galaxies with stellar mass $\sim 10^{10.5} M_\odot$ provided by Lan et al. (2014) with $0.4 < W_{\lambda 2796} < 0.8$ Å, $0.8 < W_{\lambda 2796} < 1.5$ Å, and $W_{\lambda 2796} > 1.5$ Å, as the proxy of neutral hydrogen covering fraction with $18.6 < \log N_{\text{HI}}/\text{cm}^{-2} < 19.1$, $19.1 < \log N_{\text{HI}}/\text{cm}^{-2} < 19.6$, and $\log N_{\text{HI}}/\text{cm}^{-2} > 19.6$, respectively, based on Equation (2). We emphasize that our goal is to explore how different physical mechanisms affect the gas properties by using observed properties as a guidance. Although it is possible to exhaustively search for the parameter space that can best reproduce the observed properties, we do not perform such an analysis because many parameters are degenerated with each other, as discussed in the following.

3.3.1. **Constant outflow models**

In this subsection, we demonstrate how the ensemble properties of cool gas clouds depend on the initial cloud mass function and the initial cloud velocity by using constant outflow models as examples.

**The effects of initial cloud mass function** are illustrated in Figure 7, which shows the structure of the circumgalactic medium as a function of the shape of the initial cloud mass function. Here the mean initial cloud velocity is set to be 500 km/s and a constant outflow rate of 20 $M_\odot/yr$ is assumed. Results are shown for the snapshot at 2 Gyr. We show only 10% of total number of clouds with sizes of data points reflecting 3 times of the physical sizes of clouds. The total mass in the cool circumgalactic medium is about $10^{9.5} - 10^{10} M_\odot$, with the exact value depending on the shape of the initial mass function. The results do not change significantly with time because of the replenishment of constant outflow, as shown in Figure 6. The color indicates the $N_{\text{HI}}$ the gas cloud. As can be seen, the structure of the cool CGM strongly depends on the initial cloud mass function. For a power law function with $\alpha = 0$, the CGM consists of thousands of massive clouds with $N_{\text{HI}} > 10^{20}$ cm$^{-2}$ (left panel), while the CGM produced by a power law mass function with $\alpha = -1$ contains millions of gas clouds with $N_{\text{HI}}$ ranging from $10^{18.5}$ to $10^{20.5}$ cm$^{-2}$ (middle panel). With an exponential cutoff in the massive end, the Schechter initial mass function further reduces the number of massive clouds (red dots) and produces even more small clouds (right panel).

To quantify the effects of the initial cloud mass function, we estimate the covering fraction of gas clouds as a function of $N_{\text{HI}}$ and compare the results with the observed ones in the top panel of Figure 8. The predicted covering fractions are estimated from the interceptions with clouds out of 50,000 random sightlines with parameters $\leq 250$ kpc. When multiple clouds are intercepted by a single sightline, the $N_{\text{HI}}$ is the sum of the $N_{\text{HI}}$ of individual intercepted clouds. The average neutral hydrogen gas covering fraction over the time interval between 2000 Myr and 4000 Myr produced by the power law mass functions with $\alpha = 0$ and $\alpha = -1$ are shown in purple and orange, respectively, with the bands showing...
the fluctuation of the covering fraction over time. With \( \alpha = 0 \), the gas covering fraction of \( N_{\text{HI}} < 10^{19.6} \text{cm}^{-2} \) clouds is close to zero as almost all the outflow mass is carried by massive clouds, inconsistent with the observed covering fraction shown by the blue data points. On the other hand, the number of massive clouds is suppressed and that of small clouds enhanced in the \( \alpha = -1 \) model, and the predicted covering fraction of \( N_{\text{HI}} < 10^{19.6} \text{cm}^{-2} \) is now of the same order as the observed one.

Finally, the results assuming a Schechter function with \( \alpha = -1 \) and \( M_* = 10^{5.5} M_\odot \) for the cloud mass function are shown in green color. The Schechter function redistributes the mass in massive clouds (\( M_{\text{cloud}} > M_* \)) into smaller ones, thereby further enhancing the gas covering fraction of systems with \( 10^{18.6} < N_{\text{HI}} < 10^{19.6} \text{cm}^{-2} \). The difference between the orange (power law) and green lines (Schechter function) illustrates the effect of the mass function. Such an effect can also be seen from the spatial distribution shown in Figure 7. These results demonstrate that the initial cloud function can affect the structure the gas distribution around galaxies significantly, and so can be constrained by the observed spatial gas distribution as a function of column densities.

As one can see, the outflow model with the Schechter cloud mass function can reproduce roughly the observed gas covering fraction as a function of neutral hydrogen column densities.

The effects of initial outflow velocity are shown in the middle row of Figure 8, where results obtained from three initial outflow mean velocities, 300 (cyan dotted), 500 (green solid) and 700 (blue dashed lines) km/s are plotted. As expected, the extension of the gas clouds in the halos depends on the initial velocities. Comparing to the model with 500 km/s, the model with 300 km/s is insufficient for the clouds to propagate far enough. On the other hand, increasing the mean velocity to be 700 km/s will allow more clouds to propagate to larger distances. However, since the value of \( N_{\text{HI}} \) for a fixed cloud mass decreases rapidly at large distance, as shown in Fig. 2, the clouds that propagate to large distances do not contribute significantly to the covering fraction of the relatively high-\( N_{\text{HI}} \) systems concerned here.

The initial outflow velocity in a galaxy may be constrained by the gas absorption observed toward the galaxy, i.e. through the so-called down-the-barrel observation. To do this, we assume that the effective radius of a galaxy is 5 kpc and calculate the absorption profile based on

\[
\frac{I}{I_0}(v) = 1 - f_c(v) \times (1 - e^{-\tau}),
\]

where \( I \) and \( I_0 \) are the observed flux and the continuum, respectively, \( f_c(v) \) is the covering fraction of clouds at a given velocity, and \( \tau \) is the optical depth (e.g. Jones et al. 2018). Here we consider the optical thick region where absorption lines are saturated and \( \tau \) is large. In this case the above equation can be approximated as \( 1 - f_c(v) \).

The left panel of Figure 9 shows our modeled down-the-barrel absorption. The cyan dotted, green solid, and blue dashed lines show the results with initial outflow velocity equal to 300, 500, and 700 km/s, respectively. For comparison, we also show the observed down-the-barrel strong MgII absorption of star-forming galaxies (blue histogram) from Zhu et al. (2015). We note that the observed profile include not only the absorption from outflowing gas but also from interstellar gas, while the
Figure 8. Covering fraction of gas clouds as a function of neutral hydrogen column density. The blue data points show the observed covering fraction from Lan et al. (2014). Top: Covering fraction as a function of initial cloud mass function. The results of power law mass functions with $\alpha = 0$ and $\alpha = -1$ are shown by purple and orange lines respectively. The green lines show the results from a Schechter like mass function with $\alpha = -1$ and $M_* = 10^{5.5} M_\odot$. Middle: Covering fraction as a function of mean initial cloud velocity with 300, 500, and 700 km/s shown by dotted, solid, and dashed lines, respectively. Bottom: Covering fraction as a function of time with a burst outflow model.
modeled profile includes only outflowing gas. As the interstellar gas absorption is expected to occur mostly around zero velocity, the observed blue-shifted absorption wing (< −200 km/s) is expected to be due to outflowing gas, and so can be directly compared with the modeled profile. The models with 300 and 500 km/s mean initial velocities seem able to reproduce the blue-shifted absorption profiles seen in the observation, while the model of 700 km/s produces an absorption that is stronger than observed one at high velocity (< −500 km/s). The modeled down-the-barrel absorption profile is asymmetric, consistent with the observation. This is due to two effects of the hot gas: (1) the hot gas evaporates a fraction of outflow clouds as they move out, and (2) the ram pressure decelerates the clouds even when they are falling back towards the center.

Another observable that can be used to test the model prediction is the line of sight gas velocity dispersion. To derive such quantities with our models, we first estimate the gas covering fraction as a function of velocity and obtain mock absorption spectra as a function of impact parameters. To compare and mimic the observation from SDSS (Lan & Mo 2018), we first smooth the mock absorption spectra with a Gaussian kernel with 70 km/s (SDSS spectral resolution) and then estimate the gas velocity dispersion by fitting the smoothed mock absorption spectra with a Gaussian profile. Finally, we subtract the spectral resolution in quadrature as done in Lan & Mo (2018). The right panel of Figure 9 shows the modeled line-of-sight velocity dispersion of pressure-confined outflow gas clouds. As expected, the gas velocity dispersion increases with the mean initial outflow velocity. The modeled gas velocity dispersion decreases with impact parameter due to the fact that the velocities of clouds are decelerated by both the gravity and the ram pressure of the hot gas. For clouds with \( M_{\text{cloud}} \sim 10^4 - 10^5 M_\odot \) that can reach large distances (≈ 100 kpc, as shown in Figure 3), their velocities are only tens of km/s. This is in contrast to the observed gas line of sight velocity dispersion obtained from MgII absorption lines detected in the stacked background quasar spectra around star-forming galaxies, shown by the blue data points (Lan & Mo 2018). This indicates that some other mechanisms are needed to increase the gas velocity dispersion in the halos. One possible way is to reduce the deceleration from the ram pressure effect, as discussed below.

**The effects of ram pressure** - To explore how the ram pressure affect the properties of the gas, we adjust the ram pressure efficiency \( C_\text{r} \) in Equation 4 to be only 50% of the default value. The results are shown by the light green color in Figure 9. As one can see, lowering the ram pressure efficiency does not affect significantly the down-the-barrel absorption. This is because the absorption is mostly produced by gas clouds that have just been ejected from the center (left panel of Figure 9). On the other hand, by lowering the ram pressure efficiency, the gas line-of-sight velocity dispersion is enhanced by about a factor of 1.5, closer to the observed values, as shown in the right panel of Figure 9. Changing the ram pressure efficiency does not have a big effect on the gas covering fraction, as shown in the middle panel of Figure 8, where the gas covering fractions obtained from the default ram pressure efficiency and from 50% efficiency are...
3.3.2. Burst outflow models

In addition to the constant outflow models, we show the covering fraction of gas predicted by the burst outflow model in the bottom panel of Figure 8. As shown in Figure 5, such models eject a large amount of mass into the CGM within $\sim 300 - 400$ Myr, and in 1-2 Gyr the total mass decreases by more than 50% due to heat evaporation or gas recycling. The color lines show the evolution of covering fraction as a function of time. As can be seen, the covering fraction in the inner region decreases from 100% to 10% over the period from 400 Myr to 1600 Myr. This demonstrates that to maintain the amount of mass in the CGM over a long period time, a replenishment of the circumgalactic gas is required.

3.3.3. Inflow models

We now investigate the spatial distribution of gas clouds from the inflow models. Gas inflows are expected around both star-forming and passive galaxies. We use the cool gas observed around passive galaxies as a guidance of the model prediction. The model assumes that gas clouds are initially located at 200 kpc from the halo center and fall towards the center of the halo with a constant rate of $20 \text{ M}_\odot/\text{yr}$. The system is evolved over 4
As shown in Figure 6, the amount of mass in CGM becomes stable after about 2 Gyr. The upper panel of Figure 10 shows the average covering fraction of the infalling gas clouds over a period from 2000 Myr to 4000 Myr for sightlines of different \( N_{\text{HI}} \). Results are shown for different cloud mass functions: power laws with \( \alpha = 0 \) and \(-1\) in purple and orange, respectively, and a Schechter function in green. The red and blue data points show the observed covering fraction based on MgII absorbers around passive and star-forming galaxies from Lan et al. (2014).

As in the outflow models, the covering fraction of the infalling gas as a function of the HI column density depends strongly on the shape of the initial mass function. The power law model with \( \alpha = 0 \) (purple) produces clouds only with \( N_{\text{HI}} > 10^{10.6} \text{cm}^{-2} \). With a steeper initial mass function, \( \alpha = -1 \) (orange), the covering fractions for low column density \( (N_{\text{HI}} < 10^{10.6} \text{cm}^{-2}) \) gas increase. Finally, the green lines show the covering fractions predicted by a Schechter initial mass function with \( \alpha = 0 \) and \( M_\star = 10^{5.5} M_\odot \), the same parameters as for the outflow model. As can be seen, the covering fraction of \( N_{\text{HI}} > 10^{10.6} \text{cm}^{-2} \) is suppressed and matches the observed one around passive galaxies. The covering fraction of \( 10^{19.1} < N_{\text{HI}} < 10^{10.6} \text{cm}^{-2} \) remains similar to that predicted by the power law model with \( \alpha = -1 \), with a decline beyond 150 kpc. The covering fraction of \( 10^{18.6} < N_{\text{HI}} < 10^{19.1} \text{cm}^{-2} \) increases by about a factor of 1.5, but still 10 times lower than the observed covering fraction. These results show that the inflow model can produce the covering fractions of high \( N_{\text{HI}} \) systems around passive galaxies within 100 kpc while the model fails to produce the low \( N_{\text{HI}} \) systems.

Let us have a close look at the dependence of the shape of the covering fraction on \( N_{\text{HI}} \) predicted by the Schechter model of initial cloud mass function (green lines). The covering fraction of \( N_{\text{HI}} > 10^{10.6} \text{cm}^{-2} \) (right panel) increases monotonically towards the center, while the covering fraction of \( N_{\text{HI}} < 10^{10.6} \text{cm}^{-2} \) (left and middle panels) becomes flat or even decreases slightly towards the center. This difference is due to projection effect. The monotonic increasing trend of covering fraction for \( N_{\text{HI}} > 10^{10.6} \text{cm}^{-2} \) is produced by relatively massive clouds that can survive long time and reach to the inner region of the halo where the clouds have higher \( N_{\text{HI}} \), as shown in Figure 2. In contrast, due to the evaporation, there is no small clouds that can survive long enough to reach to the center and contribute to the covering fraction of \( N_{\text{HI}} < 10^{10.6} \text{cm}^{-2} \). Thus, the covering fraction of \( N_{\text{HI}} < 10^{10.6} \text{cm}^{-2} \) within \( r_p < 100 \) kpc is due to clouds at large distances \( > 100 \) kpc but projected in the plane perpendicular to the line of sight. The projection yields to a flat covering fraction in the inner region. We note that for all the cases we have explored, the modeled covering fraction for clouds with \( 10^{18.6} < N_{\text{HI}} < 10^{19.1} \text{cm}^{-2} \) is always lower than the observed ones as shown in Figure 10. This is due to the fact that, with a given mass, only within a narrow range of locations beyond 100 kpc that clouds can have \( 10^{18.6} < N_{\text{HI}} < 10^{19.1} \text{cm}^{-2} \), as shown in Figure 2.

3.3.4. In-situ models

We now consider a scenario in which the clouds are formed in-situ in the halos. We populate clouds free-falling in the halos following a NFW and a power law, \( n(r) \propto r^{-1} \), density distributions. The cloud mass formation rate is 20 M_\odot/yr with the Schechter function of \( \alpha = -1 \) and \( M_\star = 10^{5.5} M_\odot \). The covering fraction of clouds from the NFW profile (orange) and the power law (purple) are shown in the lower panel of Figure 10.

Let us first focus on the covering fraction produced by the NFW profile. The surface mass density profile corresponding to a NFW profile is about \( \Sigma \propto r_p^{-1} \), similar to the profile of the observed covering fraction. However, with a given cloud mass, the corresponding \( N_{\text{HI}} \) decreases with \( r_p \), because of the hot gas profile shown in Figure 2. These two factors together produce a sharp decrease of the covering fraction beyond 100 kpc.

In comparison to the NFW profile, the power law distribution produces a constant surface density profile, with more mass located in the outskirt. Consequently, the profile of the covering fraction is more extended, as shown in the lower panel of Figure 10. However, the covering fraction in the inner region is lower than that predicted by the NFW profile. The inner profile of the covering fraction is also flatter due to the fact that the covering fraction is mostly contributed by clouds at larger distance in three-dimensional space. The power law distribution predicts covering fractions that are similar to the inflow models, but with an enhancement of covering fraction for high \( N_{\text{HI}} \) systems by a factor of \( \sim 1.5 – 2 \) in the inner region due to clouds directly formed in-situ close to the center. These results indicate that high \( N_{\text{HI}} \) gas systems around passive galaxies could be originated from gas infalling from the outskirt of the halo and/or gas directly formed in-situ.

4. DISCUSSION

4.1. Dependence on other model parameters

Here we discuss how the properties of the cool gas depend on other parameters in the model.

4.1.1. Dependence on hot gas

The properties of the cool clouds are clearly affected by the adopted model for hot gaseous halos. Since the hot gas properties correlate with the halo masses in our model, we illustrate such an effect by calculating the properties of the cool gas as a function of halo mass while keep other parameters intact. Figure 11 shows the dependence of the hydrogen volume density and the neutral hydrogen column density on the halo mass. For the hot gas model adopted here, the pressure of hot gas at a given radius scales with the halo mass roughly as...
Figure 11. Hydrogen volume density and neutral hydrogen column density as a function of halo mass and position. Top: Hydrogen volume density. Bottom: Neutral hydrogen column density for clouds with $10^4 M_\odot$.

$M_{\text{halo}}$, as reflected in the volume density of the cool gas shown in the upper panel. The lower panel shows the neutral hydrogen column density of clouds with a fixed cloud mass $10^4 M_\odot$ as a function of halo mass indicated by the color lines. We find that clouds with $N_{\text{HI}} > 10^{19}$ cm$^{-2}$ can only be found around halos with masses greater than $\sim 10^{11.75} M_\odot$ due to the fact that hydrogen in cool clouds becomes highly ionized when the volume density is low.

This result suggests that absorbers with high column density in neutral hydrogen e.g. $N_{\text{HI}} > 10^{19}$ cm$^{-2}$ and single-ionized gas (e.g., MgII, SiII) only exist in halos that can provide sufficient pressure-support from hot ambient gas. In addition, the high column density systems are preferentially found near the center of the halos where the pressure of the hot gas is expected to be higher. Thus, this model of pressure-confined gas cloud predicts that the incidence rate of absorbers with high column density in neutral hydrogen and in single-ionized metal elements increases with halo mass while decreases with radius. This trend is consistent with observations that high neutral hydrogen column density systems, such as strong MgII absorbers, sub-DLAs and DLAs, tend to be found around massive galaxies (e.g., Chen et al. 2010; Lan et al. 2014; Kanekar et al. 2018).

4.1.2. Evaporation factor

In Equation (8), we introduce a factor $f$ to control the efficiency of cloud mass loss due to evaporation. This factor affects the amount of mass in the circumgalactic medium by reducing the lifetime of clouds. In our model, we set $f$ to be 5%. If $f$ is taken to be 100%, i.e. 20 times as high as we adopt, the gas flow rate needs to be increased by a factor of 20 in order to maintain the same amount of the mass in the CGM. This leads to an unreasonably high value of the gas flow rate, about $400 M_\odot$/yr for the constant outflow/inflow models to match the observed covering fractions. In addition, high

Figure 12. The effect of the evaporation factor on the maximum travel distance of clouds. With 5% efficiency, clouds with 500 km/s and $10^4 M_\odot$ can reach 60 kpc with $\sim 50\%$ of initial mass, while with 100% efficiency, the clouds lose all the mass at 15 kpc.
4.1.3. Dependence on the background radiation field

The neutral hydrogen column density depends on the background radiation field. In our model, we adopt the background radiation field from Haardt and Madau (2005) at redshift 0.5. However, the radiation field evolves through time and there are more ionizing photons at higher redshifts. Such an evolution affects the neutral hydrogen column density accordingly. To illustrate the effect of background radiation field, we adopt the radiation field at different redshifts while keeping all the other parameters the same. We note that many other parameters are expected to evolve with redshifts as well, such as the hot gas properties, dark matter, etc. However, we only focus on the effect of radiation field here.

Figure 13 shows the effect of changing the radiation field from the value for \( z = 0.1 \) to that for \( z = 2 \). The three panels show the results for cloud masses \( 10^2 M_\odot \), \( 10^4 M_\odot \), and \( 10^6 M_\odot \), respectively. For small clouds (\( \sim 10^2 M_\odot \)), the effect of radiation field is significant at every location in halos. At 30-50 kpc, the hydrogen neutral fraction changes by about an order of magnitude, from \( \sim 100\% \) for \( z = 0.1 \) to \( \sim 5\% \) for \( z = 2 \). The same effect occurs for massive clouds at \( r > 50 \) kpc for \( 10^4 M_\odot \) and \( > 100 \) kpc for \( 10^6 M_\odot \). With the combination of the volume density and the thickness of clouds, massive clouds close to the center are self-shielded and, therefore, the neutral fraction is about 100% without being strongly affected by the radiation field.

Figure 14. Minimum cloud mass for \( N_{\text{HI}} > 10^{19} \text{cm}^{-2} \) as a function of redshifts. To produce systems with \( N_{\text{HI}} > 10^{19} \text{cm}^{-2} \), the cloud mass is higher at higher redshifts due to the stronger background radiation field.

By gravity and the ram pressure of the system. In contrast, for higher evaporation factors, gas clouds lose all the mass while moving outwards and the maximum distances are set by the evaporation. With 100% evaporation factor, the maximum distance the cloud can reach is only 15 kpc. This result illustrates that low evaporation factor is needed to produce the cool circumgalactic medium with reasonable parameter values.

The neutral hydrogen column density depends on the background radiation field. In our model, we adopt the background radiation field from Haardt and Madau (2005) at redshift 0.5. However, the radiation field evolves through time and there are more ionizing photons at higher redshifts. Such an evolution affects the neutral hydrogen column density accordingly. To illustrate the effect of background radiation field, we adopt the radiation field at different redshifts while keeping all the other parameters the same. We note that many other parameters are expected to evolve with redshifts as well, such as the hot gas properties, dark matter, etc. However, we only focus on the effect of radiation field here.

Figure 13 shows the effect of changing the radiation field from the value for \( z = 0.1 \) to that for \( z = 2 \). The three panels show the results for cloud masses \( 10^2 M_\odot \), \( 10^4 M_\odot \), and \( 10^6 M_\odot \), respectively. For small clouds (\( \sim 10^2 M_\odot \)), the effect of radiation field is significant at every location in halos. At 30-50 kpc, the hydrogen neutral fraction changes by about an order of magnitude, from \( \sim 100\% \) for \( z = 0.1 \) to \( \sim 5\% \) for \( z = 2 \). The same effect occurs for massive clouds at \( r > 50 \) kpc for \( 10^4 M_\odot \) and \( > 100 \) kpc for \( 10^6 M_\odot \). With the combination of the volume density and the thickness of clouds, massive clouds close to the center are self-shielded and, therefore, the neutral fraction is about 100% without being strongly affected by the radiation field.
One implication of the evolution of the background radiation field is that at a given location in the halo, the cloud mass needs to be higher at higher redshifts in order to produce a given \( N_{\text{HI}} \). Such an effect is illustrated in Figure 14, where we show the minimum mass for clouds to produce \( N_{\text{HI}} > 10^{19}\text{cm}^{-2} \) at \( r = 20 \) (blue), 50 (green) and 100 (red) kpc as a function of redshift. This result shows that the physical properties, such as mass, density, of the gas clouds giving rise to the systems can be significantly different, when comparing the absorption systems with similar column density of neutral hydrogen and/or metal species over a wide range of redshifts.

4.2. The evaporated gas in the CGM

Our model shows that a significant fraction (\( \sim 50\% \) for \( \alpha = -1 \) and \( \sim 80\% \) for a Schechter mass function) of total ejected cloud mass is evaporated. This suggests that the circumgalactic medium also contains the evaporated gas. Although the physics of the evaporated gas is not well-developed and not included in our model and in most hydrodynamic simulations, the temperature and the density of the evaporated gas are expected to be between that of pressure-confined gas clouds and that of the hot ambient gas over a certain timescale (e.g., Balbus & Potter 2016). This may be investigated with high resolution hydrodynamic simulations for individual clouds (e.g., Armillotta et al. 2017; Liang & Remming 2018; Sparre et al. 2018). For example, Armillotta et al. (2017) demonstrate that the interaction between the hot ambient gas and the pressure-confined clouds can produce evaporated and stripped gas with relatively high temperature, low density (their Figure 3 and Figure 6), low column density, and highly ionized species, such as SiIII and OVI. These results demonstrate that the evaporated gas may be responsible for a significant fraction of the relatively highly-ionized absorption line systems, such as CIV and OVI, and perhaps some low column density systems of lowly-ionized species, such as MgII. It is clearly important to understand the properties of such gas in detail in order to have a complete picture of the CGM.

4.3. Cloud-cloud collisions

In the current simulation, we do not consider the effect of collisions between gas clouds. However, the number density of clouds in the circumgalactic medium is high enough to give such events. With our constant outflow model with \( \alpha = -1 \) and \( M_* = 10^{5.5} M_{\odot} \), we find that a gas cloud ejected from the center with size about 30 pc (\( \sim 10^3 M_{\odot} \)) will collide with on average 5 other clouds between 10 to 30 kpc. Note that we count only regions beyond 10 kpc from the center to avoid high artificial collision count due to our outflow model setting. Qualitatively, we expect that cloud collisions will produce shocks that heat the clouds and dissipate the energy (e.g., McDonald & Miralda-Escudé 1999; Maller & Bullock 2004). It may also break clouds into several smaller ones and destroy them. This may change the cloud mass function in the halos and the corresponding structure of the cool CGM.

4.4. Comparisons with other studies

A universal density model - Motivated by observations, Stern et al. (2016) develop a hierarchical density structure model for the circumgalactic medium assuming that the density structure of the circumgalactic medium follows a power law distribution with high density gas embedded in the low density one. They show that this density structure can simultaneously reproduce the column densities of metal species in neutral (e.g., MgII) to highly ionized phase (e.g., OVI) at redshift 0.1. Despite that this model and our model start with different assumptions, the two predict similar MgII gas properties: cloud sizes about 50 pc and cloud masses about \( 10^2 - 10^4 M_{\odot} \) (See their Table 1).

Shattering cloudlet model - Recently, McCourt et al. (2018) propose that the pressure-confined cool gas clouds will be fragmented into tiny droplets with a characteristic scale with \( N_{\text{HI}} \sim 10^{17}\text{cm}^{-2} \) corresponding to the scale of the product of sound velocity and cooling time. This property has been demonstrated in high-resolution hydrodynamical simulations (e.g., McCourt et al. 2018; Liang & Remming 2018; Sparre et al. 2018). As discussed in McCourt et al. (2018), for a single droplet with \( N_{\text{HI}} \sim 10^{17}\text{cm}^{-2} \), the gas is optical thin and highly ionized; However, a collection of droplets can be self-shielded and produce systems with high neutral hydrogen column densities. In some sense, a single cloud in our model can be considered as a collection of droplets which are physically associated with each other and move together.

Cool gas inconsistent with the pressure equilibrium scenario - Using the data from COS on the Hubble telescope, Werk et al. (2014) characterized the physical properties of the gas around galaxies at redshift ~0.1. Using the CLOUDY simulation, they found that the detected cool gas has volume density to be \( 10^{-3} - 10^{-4} \text{cm}^{-2} \), inconsistent with the density of pressure-confined cool gas in \( 10^{12} M_{\odot} \) halos. They concluded that the scenario in which cool circumgalactic gas is in the pressure equilibrium is a poor description of the CGM. However, as shown in this study, the gas clouds in pressure equilibrium are expected to be most neutral with high neutral hydrogen column densities \( N_{\text{HI}} > 10^{18.5} \text{cm}^{-2} \), and with the covering fraction traced by strong MgII absorbers at most 20 – 30% at 50 kpc and 5 – 10% at 100 kpc. Having 44 sightlines intercepting the CGM of galaxies with a wide range of halo masses from \( 10^{11.3} \) to \( 10^{13.5} M_{\odot} \) (Tumlinson et al. 2013), it is possible that the pressure-confined gas clouds are not well sampled by the observation and most of the sightlines intercept some diffuse gas, such as evaporated gas in our model, which may have a range of temperatures
and may not be in pressure equilibrium with the hot gas. In fact, there are 4 (out of 44) COS-Halo sightlines that intercept \(N_{\text{HI}} > 10^{18.5} \text{ cm}^{-2}\), consistent with the column densities of pressure-confined gas clouds. Moreover, those sightlines are close to galaxies with relatively high stellar masses (see Figure 7 and 8 in Tumlinson et al. 2013), again consistent with the dependence of the column density on halo mass, as discussed in Section 4.1.1. We also remind that there is a projection effect: some cool gas observed by Werk et al. (2014) might be in pressure equilibrium with hot gas at large scales in 3D but projected to small scales in 2D. As we discussed in Section 3.3.2, such a configuration will produce a flat covering fraction which is similar to the covering fraction observed by the survey (Bordoloi et al. 2018). Given above, we argue that more data and advanced modeling are required to better test the scenario of the pressure equilibrium.

4.5. Limitations and directions for future work

**Hot gas** - As shown in this work, the pressure-confined cool gas properties depend on the assumed hot gas properties. In our model, we assume that the hot gas is in hydrostatic equilibrium. However, it may not reflect the real properties of hot gas as suggested by Oppenheimer (2018). In addition, we only consider the hot gas profile from a halo with \(10^{12} M_\odot\) when comparing with observations. However, the observed covering fractions are expected to be obtained from a galaxy population living in halos with a range of mass. For the future study, one should incorporate not only the hot gas properties based on different assumptions but also the distribution of halo mass, and explore how the cool gas properties depend on the assumptions for the hot gas.

Despite the importance of the hot gas, its properties around \(L^*\) galaxies are poorly constrained observationally. To understand the physics of the CGM, it is essential to better obtain the hot gas properties across a wide range of halo mass. Future X-ray missions, such as eROSITA (Merloni et al. 2012), will provide deep X-ray imaging which will enable the detection of X-ray emission from low-mass halos (see Anderson et al. 2016, for example with current missions). The Sunyaev-Zeldovich (SZ) effect can also provide information of the hot gas (e.g., Lim et al. 2018). Another interesting tool is fast radio burst, which can provide the total column density of electrons along the line of sight. With a sufficiently large sample in the near future, it is possible to constrain the total gas column density for halos with a wide range of masses (e.g., McQuinn 2014; Ravi 2018). In addition to better constraining the hot gas properties with observations, one can also model the hot gas properties across a range of density and temperature profiles, produce different realizations of the circumgalactic medium, and perform a joint analysis using multiple available observational results including X-ray, SZ, and cool gas (see Singh et al. 2018; Bregman et al. 2018, for such attempts).

**Cool gas** - we calculate the physical properties of the cool gas by assuming that the cloud temperature is a constant \(10^4\) K. However, it is expected that the cloud temperature can vary depending on the heating mechanisms. We have performed a calculation by adjusting the cloud temperature. If the cloud temperature is assumed to be 5000 K, the column density, \(N_{\text{HI}}\), will be enhanced for a given cloud mass. Therefore, for the initial mass function with \(\alpha = -1\) and \(M_* = 10^{5.5} M_\odot\) adopted in this work, the model will produce more \(N_{\text{HI}} > 10^{19.5} \text{ cm}^{-2}\) systems and overproduce the gas covering fraction for such systems. On the other hand, by increasing the temperature of clouds to be 20000 K, all the gas clouds become highly ionized with \(N_{\text{HI}} < 10^{19} \text{ cm}^{-2}\). Such a scenario cannot produce any high column density systems as observed. This suggests that the adopted cloud temperature with \(10^4\) K is perhaps reasonable for reproducing the gas properties of high \(N_{\text{HI}}\) gas absorbers. In the future, one may further explore the temperature dependence by calculating the properties of the cool CGM as a function of temperature or by assuming that the clouds are purely photoionized and using CLOUDY to solve the properties of the cool clouds.

**Survival of clouds** - One of the key assumptions in our model is that the clouds are not destroyed by the hydrodynamic instability. Although a number of studies have shown that various mechanisms can suppress the effect of hydrodynamical instability (e.g., Vietri et al. 1997; McCourt et al. 2015; Armillotta et al. 2017; Gronke & Oh 2018), it is still unclear how these mechanisms operate in reality. This problem is related to the problem of entraining the cool gas along with a hot wind (e.g., Zhang et al. 2017). However, we argue that the existence of cool gas and the evidence of contribution from outflows in the halos (e.g., Bordoloi et al. 2011; Lau & Mo 2018) suggest that either the cool gas outflows must survive over the hydrodynamic instability, as we assume in our model, or cool gas is redistributed in the halos by some other mechanisms associated with outflows (e.g., Thompson et al. 2016).

**Gas properties at large scales** - Our model has a difficulty to explain gas clouds with \(N_{\text{HI}} > 10^{19} \text{ cm}^{-2}\) beyond 100 kpc due to the low volume density of the hot ambient gas as shown in Figure 2. On the other hand, observations show that strong MgII absorbers with \(N_{\text{HI}} > 10^{19} \text{ cm}^{-2}\) do exist around galaxies beyond 100 kpc to Mpc scales and their distribution is similar to the dark matter distribution (Zhu et al. 2014; Huang et al. 2016; Lan & Mo 2018). It is, therefore, likely that some of the systems at large distances are produced by neighboring halos due to spatial clustering of halos. Such ‘two-halo’ term is not included in our current model, but should be modeled.
We develop a flexible semi-analytic framework to explore the physical properties of the cool pressure-confined circumgalactic clouds with mass from $10^8 M_\odot$ to $10^9 M_\odot$. We take into account the effects of gravity and interaction between hot gas and cool gas and model the trajectory, the lifetime, and the observed properties of the cool clouds with CLOUDY simulations. The ensemble properties of the cool CGM are explored by populating clouds following various mass functions in the halos with three origins, outflows, inflows, and in-situ formation. With this framework, we investigate how different mechanisms affect the observed properties of the cool CGM. Our results are summarized as follows:

1. The pressure-confined cool gas clouds have $N_{\text{HI}} > 10^{18.5} \text{cm}^{-2}$ with sizes about 10-100 pc similar to the observed properties of strong metal absorbers, sub-DLAs, and DLAs observed towards background spectra.

2. The interaction with hot gas plays an important role in determining the motion and lifetime of cool gas clouds; the ram pressure from the hot gas prevents most of high velocity cool clouds from escaping the system and heat evaporation destroys small clouds in about hundred million years.

3. We introduce an initial cloud mass function to populate clouds in halos and show that the structure of the cool CGM strongly depends on the shape of the mass function. With a given total mass in the CGM, a Schechter-like mass function is favored in order to produce the covering fractions that are comparable to the observed ones.

4. The ensemble properties of the cool gas clouds such as spatial distribution and kinematics are modelled by assuming three cloud origins, outflows, inflows, and in-situ formation together with an initial mass function and a velocity distribution. We show that an outflow model can produce simultaneously three properties for star-forming galaxies: the spatial distribution, down-the-barrel outflow absorption, and gas velocity dispersion. We also show that both the in-situ model and gas inflow model can produce the covering fractions of high $N_{\text{HI}}$ gas around passive galaxies that are close to the observed ones while under-produce low $N_{\text{HI}}$ systems. We illustrate the underlying physics for the success and the failure of modeling the cool CGM properties.

5. We explore how the cool gas properties depend on the assumed hot gas properties, evaporation efficiency and the ionizing radiation field. We show that the high neutral hydrogen column density systems are expected to be found in massive halos and close to the center where the hot gas pressure is expected to be high. In addition, to maintain the cool CGM with a more realistic gas flow rate, the heat evaporation factor needs to much lower than the classical efficiency.

6. Our model predicts that a significant fraction of cool gas mass is evaporated even with a low evaporation efficiency ($> 80\%$ depending on the mass function). It suggests that the CGM might cover by a huge amount of evaporated gas which plays an important role in the CGM physics and whose nature is yet be be understood.

Our results demonstrate that analytic and semi-analytic approaches are another promising way to understand and explore physical mechanisms that govern the properties of the cool CGM without limited by the numerical resolution as indicated by recent simulations and theoretical models (e.g., McCourt et al. 2018; Sparre et al. 2018; van de Voort et al. 2018; Peeples et al. 2018).

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