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Multiphase Cooling in a Large Galactic Halo

Jacob Moss and J Michael Shull

March 11, 2019

Abstract

The Cosmic Origins Spectrograph observations and The Hubble Space Telescope has detected OVI absorbers in the Circumgalactic Medium (CGM) of external galaxies, providing evidence for large gas clouds outside galactic disks. These clouds may fall into the galactic disk, replenishing the gas that is consumed by forming stars. Large-scale galactic outflows are a signature of an active star-forming galaxy and are observed at all redshifts (Veilleux et al. 2005). Exploring a radially dependent pressure distribution of the confining pressure, $P_{\text{CGM}}$, suggests that outflows reach the outer halo or exit the galaxy if we assume an outflow velocity, $v = 200 \text{ km s}^{-1}$. This could be the source of over-densities in the CGM. Cooling times $t_{\text{cool}}$ are calculated for CGM number densities in the range $10^{-4} - 10^{-6} \text{ cm}^{-3}$ and temperatures $10^4$ to $10^6 \text{ K}$. A value $t_{\text{cool}} = 35 \text{ Myr}$ for gas near the peak of the cooling curve suggests that slightly cooler, over-dense CGM gas will condense to form clouds of kpc-scale sizes. Analysis of the cooling time here provides a possible source of the observed cool CGM clouds gas. The maximum distance one kpc clouds can form in the CGM is calculated to be 150 kpc, using a beta model to describe the fall off of gas density with radius. Upon condensing, these clouds may lose pressure support and fall towards the galactic disk plane. Here, we find the minimum cloud hydrogen column density for precipitation, $N_H > 6 \times 10^{16} \text{ cm}^{-2}$. This analysis is intended to provide a better understanding of the governing principals of cloud formation in the CGM and assess CGM clouds ability to transport gas into the galactic disk.

Key words: Radiative cooling, Circumgalactic Medium (CGM), Cloud survival, Large Galactic Halos, Long Term CGM Behavior

1 INTRODUCTION

Column density measurements of absorption lines of hydrogen have shown a discrepancy between the observed baryonic mass in the universe and what is predicted from the ΛCDM cosmological model. This was one of the motivating factors that led to Spitzer (1956) predicting a galactic “corona” of hot gas at the virial temperature between a galaxy’s disk and the virial radius. Today Spitzer’s hypothesis, referred to as the Circumgalactic
Medium (CGM), is a well-known major component of a galaxy. The CGM contains a large fraction of the gas in a galaxy making it a necessary consideration to accurately describe galactic star formation rates. Furthermore, the amount of gas inside the disk, $\sim 5 \times 10^9 M_\odot$, cannot sustain the current estimate of star formation rates (SFRs) estimated to be $1 - 3 M_\odot/yr$ (Chomiuk & Povich, 2011). Thus, there must be gas transported in from the CGM to the disk.

The first evidence of CGM gas falling towards the disk was the detection of 21 cm emission at high velocities in the CGM of the Milky Way (MW). This form of light maps dense, neutral hydrogen clouds (Shull et al. 2011) in the low galactic halo. Neutral hydrogen is only present in gas at temperatures $< 30,000$ K, meaning this emission was produced by over-dense, cold objects, referred to as high-velocity clouds (HVCs). HVCs make up the coldest, densest part of the CGM. The accretion of HVCs onto the disk could provide enough gas to continually form stars at the observed rate of $2 - 3 M_\odot/yr$. CGM gas must fall out of pressure support with the surrounding gas to accrete onto the galactic disk. This happens as the gas cools and forms clouds. Thus understanding the formation of the cold gas component is important to classify galactic star formation and the movement of CGM gas which can help describe galactic evolution.

In this paper we model the formation and evolution of the cool ($< 10^5$ K) gas. Section 2 introduces number density models to describe the CGM confining pressure ($P_{\text{cgm}}$) to find the distance a galactic wind will reach in the CGM based on confining pressure arguments. This wind could act as seeds for cloud formation depending on its range of influence. Section 3 develops the process of cloud formation due to thermal instabilities and constraints on cloud precipitation. Section 4 addresses cloud interactions. Section 5 concludes by describing effects on the long-term behavior of the CGM and implications of this work on future CGM research.

## 2 Pressure Analysis

### 2.1 Constant Pressure

Galaxies moves gas out of the disk via galactic outflows. Over-densities in the CGM can be predicted by estimating where the gas in these outflows settle. Our first problem is to find the radius ($R_{\text{wind}}$), where the ram pressure of the wind, $P_w = \rho_w v_w^2$, is equal to the confining pressure of the CGM. Here $\rho_w$ is the gas mass density of the wind and $v_w$ represents the velocity of the wind. As a first approximation we take the pressure of the CGM to be constant, $P_{\text{cgm}} = n k T$, where $n$ is the total particle number density (H, He, and $e^-$) the hydrogen number density is $n_H = 10^{-5} \text{ cm}^{-3}$, halo virial temperature is taken to be $2 \times 10^6$ K, assuming a He/H fraction of 0.0833 by number, and scaling the gas pressure $P_{\text{cgm}}/k$ to a standard value of 40 cm$^{-3}$K. The mass-loss rate of an outflow into a solid angle ($\Omega_w$) is $\dot{M} = \Omega_w r^2 \rho_w v_w$ where we allow for conical outflow ($\Omega_w \leq 4\pi$). We use this relation to find a value for $\rho_w$ ($v_w = \text{const} \rightarrow \rho \sim 1/r^2$) where the two values will equate at
some distance away from galactic center. We assume that the ram pressure starts off larger than the thermal pressure at the edge of the Galactic star-forming disk. We relate mass-loss rate to star-formation rate (SFR) through a mass-loading factor $\beta_m = \dot{M}/\text{SFR} \approx 1$, with a standard SFR of $(10 \, M_\odot \, \text{yr}^{-1}) \dot{M}_{10}$. For wind speeds $v_w = (200 \, \text{km s}^{-1}) v_{200}$, we find

$$r_{\text{wind}} = \left( \frac{\dot{M}_w v_w}{P_{\text{CGM}}\Omega_w} \right)^{1/2} = (140 \, \text{kpc})(\dot{M}_{10} v_{200})^{1/2}(P_{40} \Omega_4)^{-1/2}.$$

(1)

Here, 140 kpc lies within the gravitational radius of a reasonably sized galaxy of mass $M_{\text{gal}} > 10^{11} \, M_\odot$. Therefore, if $\Omega = 4\pi$ steradians the gas expelled by the winds is recycled back into the disk on a free-fall timescale of $t_{\text{ff}} \approx 1 - 2 \, \text{Gyr}$. The coverage of an outflow is observed to be between 10-40% of $4\pi$ (Veilleux et al. 2005). Evaluating (1) with $\Omega_w = 30\%$ of $4\pi$ increases $R_{\text{wind}}$ to 255 kpc, past the virial radius for the MW (200 kpc). Both calculations suggest that these outflows should interact with the CGM and could be the source of CGM over-densities.

### 2.2 Power Law

The particle number density is thought to fall off with increasing radius. This will also affect the gas pressure as $P_{\text{CGM}} \propto n$. Assuming a more accurate power law fall off, $P_{\text{CGM}}(r) \approx P_0(r/r_0)^{-\beta}$ (Sarazin 1986), the method of analysis changes. On the next page Figure 1 is a plot of the two pressure equations against each other for some values of $\beta$ and $r_0$ to find the intersection, representing the radius where the pressures are equal. Values for $r_0$, the scaling radius, vary from 100-150 kpc, $P_0/k_B = 40 \, \text{cm}^{-3} \, \text{K}$, and $\beta = 1.0 - 1.8$. The calculated radii are tabulated in Table 1.

<table>
<thead>
<tr>
<th>Beta value $\beta$</th>
<th>$R_{\text{wind}}$ $(r_0 = 100 , \text{kpc})$</th>
<th>$R_{\text{wind}}$ $(r_0 = 125 , \text{kpc})$</th>
<th>$R_{\text{wind}}$ $(r_0 = 150 , \text{kpc})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>192 kpc</td>
<td>154 kpc</td>
<td>128 kpc</td>
</tr>
<tr>
<td>1.1</td>
<td>206 kpc</td>
<td>157 kpc</td>
<td>126 kpc</td>
</tr>
<tr>
<td>1.2</td>
<td>226 kpc</td>
<td>162 kpc</td>
<td>123 kpc</td>
</tr>
<tr>
<td>1.3</td>
<td>254 kpc</td>
<td>168 kpc</td>
<td>120 kpc</td>
</tr>
<tr>
<td>1.4</td>
<td>297 kpc</td>
<td>176 kpc</td>
<td>115 kpc</td>
</tr>
<tr>
<td>1.5</td>
<td>369 kpc</td>
<td>189 kpc</td>
<td>109 kpc</td>
</tr>
<tr>
<td>1.6</td>
<td>511 kpc</td>
<td>209 kpc</td>
<td>101 kpc</td>
</tr>
<tr>
<td>1.7</td>
<td></td>
<td>248 kpc</td>
<td></td>
</tr>
<tr>
<td>1.8</td>
<td></td>
<td>350 kpc</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1: The blue curve represents the ram pressure, the orange curve is the CGM confining pressure, and the intersection point is marked by the green x. General trend is that the confining radius increases as $\beta$ increases.
When $P_w = P_{\text{CGM}}$, values of $r$ all increase as $\beta$ increases. The only change occurs when $r_0$ is greater than the constant-pressure solution in the previous section. Since $r_0$ is past the intersection point, increasing $\beta$ will decrease the distance the wind travels through the halo. Observing Table 1 with our improved approximation, we still expect the winds to interact with the CGM as it passes through. We assume $\Omega_w = 4\pi$ in this analysis.

### 2.3 Beta Model

The beta model is also a common way to estimate the number density in the CGM. It takes the form of

$$n(r) = n_0 \left(1 + \frac{r^2}{r_0^2}\right)^{-\frac{3\beta}{2}},$$

where $r_0$ is the core radius and $n_0$ is the hydrogen number density near the core radius. Miller & Bregman (2013) show that a spherically symmetric beta model works just as well as a variation that considers the geometry of the galaxy, so we use it for simplicity. Substituting for number density in $P_{\text{CGM}} = nkT_{\text{CGM}}$, and equating that to $P_w$ gives us

$$n_0 \left(1 + \frac{r^2}{r_0^2}\right)^{-\frac{3\beta}{2}} kT_{\text{CGM}} = \dot{M}v \frac{\Omega_w}{r^2}.$$  

Defining a dimensionless variable $x = r^2/r_0^2$, the square of the ratio of $r$ over the core radius, we can re-write the equation as,

$$\frac{x}{(1 + x)^{3\beta/2}} = \frac{\dot{M}v}{\Omega_w nkT_r^2}.$$  

The right-hand side represents the relationship between $P_w$ and $P_{\text{CGM}}$ at the core radius, and $\beta$ describes how the $P_{\text{CGM}}$ falls off with increasing radius. Analyzing the right hand side along with the parameter $\beta$ describes every possible outcome of the wind. When the right-hand side is greater than one, and $3\beta/2$ is also greater than one, at the core radius $P_w > P_{\text{CGM}}$ and $P_{\text{CGM}}$ falls off faster than $P_w$. If the wind gets past the core radius, it will escape the galaxy. When the right-hand side is greater than one, but $3\beta/2$ is less than one. $P_w > P_{\text{CGM}}$ at $r = r_0$ but then $P_{\text{CGM}}$ falls off slower and the pressure functions will intersect. Now the dimensionless radial parameter (x) must be greater than 1, and this tells us the solution lies outside of the core radius, and the wind stops in somewhere in the CGM. The other two scenarios with the right-hand side less than one imply that the wind does not make it out of the core radius which disagrees with our initial assumption. Thus, they are not discussed further.

Our pressure analysis of a galactic outflow suggests mixing with most if not all of the CGM. Observations have shown that outflows are multi-phased, spanning temperatures from $10^8$ K to 100 K (Zhang 2018). If the outflows are present in the CGM, the $10^4 - 10^5$
K gas may serve as seeds for cloud formation. If clouds are already forming, the winds could disrupt cloud formation as the wind passes through the cloud.

3 Inhomogeneous Considerations

3.1 Cloud Cooling/Size

We now shift focus to the thermal instability of the gas in the CGM. This is likely to be the primary method of cooling in the CGM. There is observational evidence that supports dense, cooler gas forming in galaxy halos with the detection of OVI absorption in QSO sight-lines (Tumlinson et al. 2011). Cool gas may form out of the outflows discussed in the Section 2. Gas in a halo cools at a speed governed by the radiative cooling rate per unit volume \((\text{erg cm}^{-3} \text{s}^{-1})\), leading to a characteristic cooling time \(t_{\text{cool}}\):

\[
t_{\text{cool}} = \frac{3nkT}{n_ne_nH \Lambda(T)}
\]

Figure 2: Shows Radiative cooling rate for different elements assuming solar metallicity (Gnat & Ferland 2012).

The cooling function used, \(\Lambda(T)\), shown in Figure 2 (Gnat & Ferland 2012) parametrizes the rate \((\text{erg cm}^3 \text{s}^{-1})\) at which gas loses its thermal energy at a given temperature. The
cooling function also depends on metallicity, observations of CGM metallicity range from 10\%-30\% solar metallicity, $Z_{\odot}$ (Wakker et al. 1999; Collins et al. 2003). Here we take $(Z/Z_{\odot}) = 0.2$. Thermal instabilities in over-dense gas start to occur when the cooling function becomes substantial at $T < 10^6$ K. Over-dense perturbations then cool at an increasingly faster rate as the temperature falls from $10^6$ K to $10^5$ K with a rising cooling curve. The cloud is still in pressure equilibrium with $nT$ constant ($n \sim T^{-1}$). From $10^6$ K to $10^5$ K we scale $\Lambda(T) \propto T^{-0.7}$, which gives a temperature dependence of $t_{\text{cool}} \propto T^{2.7}$.

Scaling $T = (10^6$ K) $T_6$, just below the virial temperature, we approximate a linear scaling with metallicity and express $\Lambda(T) \approx (2 \times 10^{-22}$ erg cm$^3$ s$^{-1}$) $(T/T_6)^{-0.7}$ $(Z/Z_{\odot})$ with $T_0 = 10^6$ K, and $n = (10^{-4}$ cm$^{-3}$) $n_{-4}$ (about 10 times the average halo particle density),

$$t_{\text{cool}} = \frac{3kT}{n\Lambda(T)} = (656 \text{ Myr}) (T_6)^{1.7} \left(\frac{Z}{0.3Z_{\odot}}\right) (n_{-4})^{-1}$$

(6)

For gas at the peak of the cooling curve ($3 \times 10^5$ K), we find $t_{\text{cool}} = 25$ Myr ($n_{-4}$). This shows the rapid decrease in $t_{\text{cool}}$ as the gas cools. The temperature dependence increases to $T^{3.2}$ when we consider the cooling length, $\ell_{\text{cool}} = c_st_{\text{cool}}$, with $c_s = \sqrt{kT/\mu}$. Here we take $\mu = 0.609 m_H$ for fully ionized monatomic gas with $n_{\text{He}}/n_H = 0.1$. This gives us an estimate of the cloud size,

$$\ell_{\text{cool}} = c_s \times t_{\text{cool}} = \sqrt{\frac{k_BT}{\mu}} \frac{3kT}{n\Lambda(T)} = (78 \text{ kpc}) (T_6)^{2.2} (n_{-4})^{-1}.$$

(7)

This simple estimate illustrates the dramatic decrease of $\ell_{\text{cool}}$ when comparing values for hot, warm, and cool halo gas. We find $\ell_{\text{cool}}(T_6) = 77.8$ kpc, $\ell_{\text{cool}}(T_{\text{peak}} = 3 \times 10^5$ K) = 1.65 kpc, and $\ell_{\text{cool}}(T = 10^5$ K) = 50 pc, where $T_{\text{peak}}$ is the peak of the cooling function. The strong temperature dependence of $t_{\text{cool}}$ and $\ell_{\text{cool}}$ suggest cloud formation for gas close to the peak of the cooling curve, $T_{\text{peak}} \approx 1 - 3 \times 10^5$ K. In other words, clouds are likely to condense from gas a little bit cooler than average and slightly over-dense.

### 3.1.1 Beta Model Effects on Cooling

For CGM gas with $n = 10^{-4}$ cm$^{-3}$ and $T \approx T_{\text{peak}}$, the cooling length $\ell_{\text{cool}}$ suggests clouds of kilo-parsec size. If the warm gas starts out in hydrostatic equilibrium with the hot gas in the halo then the warm component will be $\sim 10$ times more dense. Using a beta model with Miller & Bregman (2013) parameters, $\beta = 0.71$, $n_0 = 0.46$ cm$^{-3}$, and $r_c = 0.35$ kpc, we can estimate a maximum distance where we expect kilo-parsec clouds to form in the CGM by finding the radius where $n = (10^{-5}$ cm$^{-3}$) $n_{-5}$ for the hot gas. For $r \gg r_0$ the beta model simplifies to

$$n(r) \simeq n_0 \left(\frac{r}{r_0}\right)^{-3\beta}.$$

(8)
In their model, number density of \( n \simeq 10^{-5} \ \text{cm}^{-3} \) occurs at \( r \simeq 54 \ \text{kpc} \) for hot gas, suggesting that average CGM gas will not form kpc-scale clouds past this radius. If we consider gas that is 10 times over-dense in the CGM, the maximum formation radii extends to \( \sim 160 \ \text{kpc} \).

### 3.1.2 Enthalpy

As the gas cools, \( R, n, \Lambda(T) \), and \( t_{\text{cool}} \) all change. This cooling, together with pressure-work on the cloud can be modeled by considering the change in enthalpy as the gas radiates away energy while cooling,

\[
\frac{dH}{dt} = n_e n_H A(T) = \frac{d}{dt} \left[ \frac{5}{2} n_{\text{tot}} kT \times \frac{4}{3} \pi R^3 \right].
\]

Here we assume spherical symmetry for a cloud of radius \( R(t) \), pressure equilibrium, constant cloud mass (\( nR^3 = \text{constant} \)), total particle density \( n_{\text{tot}} = 2.3 n_H kT \) (He/H=10%, fully ionized), and a cooling curve dependence of \( \Lambda(T) = \Lambda_0 (T/T_0)^{-0.7} (Z/Z_\odot) \) for \( 10^4 \ \text{K} \leq T \leq 4 \times 10^6 \ \text{K} \). Thus, \( n \sim T^{-1} \sim R^{-3} \), allowing us to solve

\[
R^7 \frac{dR}{dt} = - \left[ \frac{\Lambda_0 n_0^2 R_0^8}{14.375 P_0} \right] = \text{Constant}
\]

where we approximate \( R^{-7.1} \approx R^{-7} \). This yields three equations,

\[
R(t) = R_0 \left[ 1 - \frac{t}{t_{\text{cr}}} \right]^{1/8},
\]

\[
T(t) = T_0 \left[ 1 - \frac{t}{t_{\text{cr}}} \right]^{3/8},
\]

\[
n(t) = n_0 \left[ 1 - \frac{t}{t_{\text{cr}}} \right]^{-3/8}
\]

with

\[
t_{\text{cr}} = 1.80 \left( \frac{kT_0}{n_0 \Lambda_0} \right) \approx (39.4 \ \text{Myr}) T_0 n_{-3}^{-1} \left( \frac{Z}{Z_\odot} \right)^{-1}
\]

that describe how \( R, T, \) and \( n \) vary as the gas rides up the cooling curve from \( 10^6 \ \text{K} \) to \( 10^5 \ \text{K} \). This relation is only valid when the cooling curve can be well approximated as \( \Lambda(T) = \Lambda_0 (T/T_0)^{-0.7} (Z/Z_\odot) \). After the gas cools past this range, \( \Lambda(T) \) drops sharply, increasing \( t_{\text{cool}} \).
3.2 Cloud Covering Factor

One can estimate the area covering factor of clouds using density and mass ratios of the clouds relative to the CGM and assuming a uniform cloud density. These quantities are useful to conceptualize detection rates of OVI in galaxy halos. If we know the detection rate of OVI, a range for the number of clouds expected in a halo can be found. The density ratio, the contrast between the cloud:intercloud medium in pressure equilibrium (\(10^4\) K cloud and \(10^6\) K CGM), is taken to be 100:1 (\(\Delta_{100}\)) and the mass ratio to be 1:9 (warm/cool to hot). Faerman et al. (2016) find that \(\sim 88\%\) of CGM gas mass is from the hot component. As a first estimate for the covering factor, we set \(R = 1\) kpc to find a cloud mass,

\[
m_{cl} = \frac{4\pi}{3} R^3 n\Delta_{100}\mu = (6.3 \times 10^4 \, M_\odot)(R_{kpc})^3 (n_{-5}).
\]

(15)

This formula assumes an ambient CGM number density of \(n = (10^{-5} \text{ cm}^{-3}) n_{-5}\). Tumlinson et al. (2017) predict a halo hot component gas mass range of \(1.5 - 3.3 \times 10^{10} \, M_\odot\) for luminous galaxies for halos 200 kpc in radius. We scale the total CGM gas mass that encompasses all the gas phases to \(M_{\text{cgm}} = 10^{10} \, M_\odot\) for a halo that reaches 150 kpc. The number of clouds is then \(N_{cl} = 1.6 \times 10^4\). This gives an area covering factor of 71\%. Tumlinson et al. (2013) suggest that the observed area covering factor is close to one.

Note that cloud size generally increases as \(\ell_{cool} \propto n^{-1}\) as one gets farther away from the halo. We now estimate the area filling factor, \(f_a\), by defining three annular regions in the CGM (1) \(r = 150 - 100\) kpc, (2) \(r = 100 - 50 \) kpc, and (3) \(r = 50 - 25\) kpc. In these regions we use different cloud sizes, (1) \(R = 1\) kpc, (2) \(R = 500\) pc, and (3) \(R = 150\) pc. The number of clouds can be estimated as,

\[
N_{cl} = \frac{\text{total warm component gas in region}}{\text{mass of one cloud in region}} = \frac{V_{\text{ann}} M_{\text{cgm}}}{\frac{4\pi}{3} R^3 \rho_{cl}}.
\]

(16)

\(V_{\text{ann}}\) is the annular volume of the CGM, \(V_{\text{ann}} = (a^3 - b^3) \times 0.1/(150^3 - 25^3)\) and, \(a\) and \(b\) are the radii that bound the specific region where \((a,b)\) have units of kpc. Here, \(\rho_{cl} = n\Delta_{100}\mu\) is the mass density of the cloud with \(\mu = 1.4\). We find \(N_{cl} = 11,408\) \((R = 1\) kpc\), \(N_{cl} = 20,353\) \((R = 500\) pc\), and \(N_{cl} = 142,825\) \((R = 150\) pc\), for the number of clouds in a given region. Given the number of clouds in the three regions, we can find an area covering factor, taking into account contributions from all regions. Thus,

\[
f_a = \frac{N_{cl} R^2}{a^2 - b^2}
\]

(17)

gives an area covering factor of 88\%, showing that including a variable cloud size gives an area filling factor in closer agreement with our observations. The annular volume \(V_{\text{ann}}\) has a bias towards the outer regions, as we expect particle number density to fall as distance away from the halo increases. This bias increases the number of big clouds calculated as
it overestimates the CGM mass in these outer regions. The calculation also doesn’t take into consideration that bigger clouds are generally farther away from the disk than smaller ones. Including this subtlety would increase the value calculated for $f_a$.

### 3.3 Cloud precipitation

The clouds will contract while cooling if they are in pressure equilibrium with the surrounding gas. This effect decreases the difference in pressure between the top and bottom of the cloud, potentially causing the cloud to fall out of hydrostatic equilibrium with the hot ambient halo gas. To estimate when a cloud will lose pressure support in the halo, we find where the force of gravity on the cloud, $F_G$, is greater than the force of the pressure difference between the top and the bottom of the cloud, approximated as a 1D slab,

$$M_{\text{slab}} g(z) > (P_1 - P_2) \Delta A.$$  \hspace{1cm} (18)

We assume the enclosed galactic mass is dominated by a spherically symmetric DM halo so $g(z) = g(r)$ which is a good assumption for $r \gg r_{\text{disk}}$. For flat rotation curves, $M(r) \propto r$ so we use $M(r) = M_0(r/r_0)$ to find the enclosed mass with $M_0 = 3.89 \times 10^{11} M_\odot$, $r_0 = 50$ kpc, and $r_{\text{vir}} = 200$ kpc. Callingham et al. (2019) find enclosed masses for the Milky Way to be, $M_{\text{vir}} = 1.17 \times 10^{12} M_\odot$ and $M(r = 20$ kpc) = 0.12$M_{\text{vir}}$. We assume the cloud is a slab with dimensions, area=$\Delta A$ and height=$\Delta z$. The mass of the cloud is then $M_{\text{slab}} = \mu n_H \Delta A \Delta z$. We take $\mu = 1.333 m_H$ using a primordial ratio $(\text{He}/H) = 0.0833$ by number. Rewriting cloud hydrogen column density, $N_H = n_H \Delta z$, the criterion for cloud precipitation yields,

$$N_H > \frac{(P_1 - P_2)}{\mu g(z)},$$  \hspace{1cm} (19)

with $P_1$ defined to be pressure at the lower side of the cloud. Assuming an isothermal medium, $T = 10^6$ K, means the ambient pressure differences are due to a changing number density of the CGM, $n(r)$. Here we define $n(r)$ using the $r \gg r_0$ approximation of a beta model with $r_0 = 50$ kpc, $n_0 = 2 \times 10^{-5}$ cm$^{-3}$ and $\beta = 0.71$ (Miller & Bregman 2013). For this calculation we assume the cloud to be on the polar axis so $n(z) = n(r) \approx n_0(r/r_0)^{-3\beta}$. Thus $\Delta P = kT \Delta n$ with

$$\Delta n = \left| \frac{dn}{dr} \right| \Delta z = \left( \frac{3\beta n_0}{r_0} \right) \left( \frac{r}{r_0} \right)^{-3\beta - 1} \Delta z.$$  \hspace{1cm} (20)

The minimum cloud column density for precipitation is then,

$$N_H > \frac{3\beta n_0 kT}{\mu r_0 g(z)} \left( \frac{r}{r_0} \right)^{-2.13} \Delta z = (5.94 \times 10^{16} \text{ cm}^{-2}) \left( \frac{r}{50 \text{ kpc}} \right)^{-2.13} \left[ \frac{P_0/k}{45 \text{ cm}^{-3} \text{ K}} \right]$$  \hspace{1cm} (21)
with \( P_0 \) the pressure at \( r_0 = 50 \text{ kpc} \) and a slab thickness \( \Delta z = 1 \text{ kpc} \). Interestingly, \( N_H \) scales with the number density profile of the CGM. The calculated \( N_H = 6 \times 10^{16} \text{ cm}^{-2} \) is similar to the lowest-column HVCs which can extend up to \( N_H \sim 10^{19} - 10^{20} \text{ cm}^{-2} \) (Wakker et al. 1999; Collins et al. 2003). For cloud with \( R = 1 \text{ kpc} \) and \( n = 10^{-3} \text{ cm}^{-3} \), \( N_H = 3 \times 10^{18} \text{ cm}^{-2} \).

### 4 Cloud Interactions in the CGM

#### 4.1 Infall/Stripping

Consider a 1 kpc cloud with \( n_{cl} = 10^{-3} \text{ cm}^{-3} \) at a distance of 50 kpc away from galactic center on the polar axis using the section 3.3 formulation. Thus, \( a(r) \approx g(r) = -(GM(r)/r^2) \) which we use to find a timescale for cloud accretion onto the halo, \( t_{dyn} = 533 \text{ Myr} \) absent other forces. Typically, \( t_{dyn} \) is calculated using an NFW profile to model the enclosed mass, \( M(r) \), for a galaxy (Navarro et al. 1997),

\[
M_{\text{vir}} = \left( 4\pi \rho_0 r_s^3 \right) \left[ \ln(1 + c) - \frac{c}{1 + c} \right] \tag{22}
\]

and

\[
\rho(r) = \frac{\rho_0}{(r/r_s)[1 + (r/r_s)]^2}, \tag{23}
\]

with the scaling radius, \( r_s = R_{\text{vir}}/c \) (Navarro et al. 1997) and \( M_{\text{vir}} = 1.17 \times 10^{12} \text{ M}_\odot \) (see pages by Callingham et al. 2019). The concentration parameter, \( c \), decreases with increasing halo masses and ranges from 5-20 (Shull et al. 2014). We use \( c = 10 \) (Navarro et al. 1997). From the NFW profile we find \( M(50 \text{ kpc}) = 6.1 \times 10^{11} \text{ M}_\odot \) and \( t_{dyn} = 426 \text{ Myr} \).

We can also find the clouds velocity, \( v(r) \), given \( a(r) \). In the far halo \( \rho \propto r^{-2} \) so \( M \propto r \). Using \( M(r) = M_0 (r/r_0) \) to model the enclosed mass within radius \( r \), we evaluate the first integral of motion assuming initial conditions \( \dot{r} = 0 \) and \( r_0 = 50 \text{ kpc} \),

\[
\frac{1}{2} \dot{r}^2 = - \int_{r_0}^{r} \frac{GM(r)}{r} dr. \tag{24}
\]

We find the cloud velocity as a function of radius away from galactic center to be

\[
\dot{r} = - \left[ \frac{2GM_0}{r_0} \right]^{1/2} \sqrt{\ln(r_0/r)}. \tag{25}
\]

At first glance it might seem odd that the cloud velocity is so weakly dependent on radius \( r \). However, as you vary the location of the cloud, \( r \), its velocity will not change much if the cloud is moving relatively fast. For \( r = 25 \text{ kpc} \), \( \dot{r} = 180 \text{ km s}^{-1} \), measured HVC velocities range from 100 – 300 km s\(^{-1}\) (Tumlinson et al. 2017).

As clouds condense, fall out of hydrostatic equilibrium, pick up speed, and fall into the disk the ambient CGM will start to disrupt the structure of the clouds. One can estimate
when this effect becomes relevant by finding the distance at which the ram pressure exceeds the clouds internal pressure,
\[ \rho_{\text{halo}} r^2 \geq n_{\text{cl}} k T_{\text{cl}}, \]  
with \( \rho_{\text{halo}} = \mu n_H \), and \( T_{\text{cl}} = 10^4 \) K. These terms are equal at \( r = 44 \) kpc, so after traveling just 6 kpc, the ram pressure will start to disrupt the cloud if it starts 50 kpc away from the galactic center.

### 4.2 Cloud collision rates

To estimate the role of cloud-cloud interaction we can define a collision rate of
\[ n_{\text{cl}} \sigma_{\text{cl}} v_{\text{rel}} = 8.22 \times 10^{-18} \text{ s}^{-1}, \]
1.24 \times 10^{-17} \text{ s}^{-1}, and \( 6.248 \times 10^{-17} \text{ s}^{-1} \) for regions 1) 150-100, 2) 100-50, and 3) 50-25 kpc respectively from Section 3.2, with \( n_{\text{cl}} = N_{\text{cl}}/V_{\text{halo}} \), \( v_{\text{rel}} = 100 \) km s\(^{-1}\), and cloud cross-section \( \sigma_{\text{cl}} = \pi R^2 \). Here we scale \( R = R_{\text{kpc}} \). Collision times, \( t_{\text{col}} = 3.9 \) Gyr, 2.6 Gyr, and 508 Myr, implying that collisions happen more frequently in the inner halo.

### 4.3 Cloud Momentum

Calculating how much momentum is captured in the wind-cloud encounter can be done by examining the mass intercepted. We assume that the wind sweeps up all of the mass of the cloud. We take the velocity of the wind with respect to the cloud to be \( v_w = 300 \) km s\(^{-1}\) and the number density of the cloud \( n_{\text{cl}} = \Delta \times n \) where the density of the CGM is \( n \) and \( \Delta = (n_{\text{cl}}/n) = 300 \) \( \Delta_{300} \) represents the density contrast between the cloud and the CGM. The cloud radius is defined to be \( R = 500 \) pc and the wind meets the cloud at \( r = 50 \) kpc. The mass of the cloud is then,
\[ m_{\text{cl}} = (4/3\pi R^3)(1.4 m_H)n_{\text{cl}} = (1.8 \times 10^5 \ M_\odot)(R_{500})(n_{\odot})(\Delta_{300}). \]

When the wind impacts the cloud it sends a slow shock through the cloud. This is how fast the wind transits the cloud. From conservation of momentum flux, the velocity of the shock, \( v_s \), is equal to the sound speed \( c_s = v_w/\sqrt{\Delta} \). The time for the slow shock to cross the cloud is defined by, \( t_{\text{cr}} = (2R/v_s) \simeq 57 \) Myr. To find the mass density of the wind we express the wind mass-loss rate as \( \dot{M} = 4\pi r^2 \rho_w v_w \). Then by relating wind mass-loss rate to \( \dot{M} \) as done in section 2.1, \( \dot{M} = \beta_m \times \text{SFR} \), we can solve for \( \rho_w \). Multiplying \( \rho_w \) by the solid angle covered by the cloud, \( \Delta \Omega = \Delta A/r^2 \), and the cloud crossing time \( t_{\text{cr}} \) gives an expression for how much mass intercepts the cloud, \( \Delta m = \rho_w t_{\text{cr}} \Delta \Omega \). Comparing the two masses tells us that the mass of wind is approximately 7% the mass of the cloud. This means if the wind sweeps up all the cloud’s mass, the new system moves at a velocity less than 7% of its original velocity with respect to the cloud. The momentum lost is largely dependent on the cloud’s density and fluid dynamics of the wind flow past the cloud. If the cloud radius was 1 kpc instead of 500 pc, the cloud crossing time would increase to
115 Myr. Now the question arises whether the wind even lasts that long; Bergvall et al. (2016) found a median starburst age of 70 Myr. That starburst lifetime plus the 40 Myr it takes for the last star in OB association to explode as a supernova is now the important timescale in finding the mass intercepted by the wind.

However, it is more likely for the wind to affect the structure of the cloud, possibly even shredding the cloud as it passes through. In numerical simulations of interactions between SN blast waves and ejecta, Silvia et al. (2010) found that clouds are shredded in \( \sim 2 \) cloud-crushing times. The amount swept up by a relatively dense wind is dependent on the velocity of the shock, \( v_{\text{shock}} = c_s M(1 - \rho_m/\rho_{\text{shock}}) \). Conveniently, \( t_{\text{cr}} \) can also stand for cloud-crushing time, defined by the same equation as the cloud crossing time if the cloud is believed to be crushed as opposed to swept up. This means that winds could stall cloud formation as they pass through the CGM.

5 Conclusions and Discussion

This paper first introduced a variety of \( P_{\text{cgm}} \) pressure models to determine the radial extent of a large-scale galactic outflow, assuming the wind makes it out of the disk. Observations suggest that the CGM gas contains metals, which is strong evidence that gas from the disk has mixed with the CGM through some form of Galactic feedback. Using a constant pressure, \( P_{\text{cgm}} \), we found that the wind stalls at around 140 kpc. This distance increases when \( P_{\text{cgm}} \) falls off with radius as a power law, \( P_{\text{cgm}}(r) = P_0 (r/r_0)^{-\beta} \). If \( 3\beta/2 \) was greater than one, in some cases it implied that the wind would escape the galactic halo. Both pressure models indicate that the outflow mixes with the CGM leading to pockets of over-densities in the CGM. These pockets may be centers of cloud formation.

In section 3.1, we found \( t_{\text{cool}} = 656 \) Myr \( \ll t_H \), the Hubble time in slightly over-dense halo regions, even for gas close to the virial temperature, \( 10^6 \) K. Thus unless there is a heating source, the CGM is constantly forming the warm, \( \sim 10^5 \) K, component. Furthermore, \( t_{\text{cool}} \) has a very strong temperature dependence, \( t \propto T^{2.7} \) over a temperature range from \( 4 \times 10^6 \) K down to \( 10^5 \) K so clouds will form fast from the warm component in the CGM. From \( t_{\text{cool}} \) we defined a cooling length, \( \ell_{\text{cool}} = c_s \times t_{\text{cool}} \) which estimates the cloud size for gas at a given temperature and number density. The parameter \( \ell_{\text{cool}} \) and \( t_{\text{cool}} \) suggest that smaller clouds form closer in more frequently, and faster. The opposite is true for larger clouds. Noting the number density fall off in accordance with the beta model and assuming an upper limit for cloud size of \( R = 1 \) kpc, the maximum distance, \( r \), into the halo that supports cloud formation is \( \sim 150 \) kpc. Using the precipitation criterion in section 3.3 we find that a cloud with \( R = 1 \) kpc and \( r = 50 \) kpc will fall in towards the galactic disk. The main conclusions of the paper are as follows.

1. If outflows are present, mixing will occur with the CGM as it passes through. Depending on the timing, winds could either speed up the early stages of cloud formation or shred the clouds as they pass by.
2. Both $t_{\text{cool}}$ and $\ell_{\text{cool}}$ have strong temperature dependences. Thus, any gas that is slightly cooler than the virial temperature will cool rapidly. This makes warm metal enriched gas very important for forming clouds.

3. Clouds are unlikely to form outside radius $r \approx 150$ kpc in the halo, because $n(r) \sim r^{-2.14}$ for the beta model with parameters, $\beta = 0.71$, $n_0 = 0.46 \text{ cm}^{-3}$, and $r_c = 0.35$ kpc (Miller & Bregman 2013).

4. We expect newly formed clouds to fall out of hydrostatic equilibrium with surrounding gas and “rain” down on the host galaxy. Ram-pressure stripping of the cloud will then quickly disrupt the in-falling cloud.

The intent of this paper is to model the formation and development of clouds in the galactic halo. Many simply see CGM as merely a passive region in between the Intergalactic Medium (IGM) and the galactic disk. This paper shows in accordance with current observations of galactic parameters the CGM is suitable environment to form clouds. The fuel for CGM cloud formation could be provided by gas flowing out in the form of galactic winds and settling to form over-dense regions or the cooling of the CGM’s hot component, $t_{\text{cool}} = 656 \text{ Myr} \left( T_6 \right) \left( n - 4 \right)$. Once clouds have formed they are unstable and will fall towards the disks. Now questions arise like, how the timing of CGM cloud formation and accretion relates to other galactic processes such as Outflows or SFRs and can we quantify the accretion rate of CGM clouds onto the disk to account for disk gas lost due to star formation?

The time it takes CGM clouds to form, $t_{\text{cool}}$, ranges from 25-656 Myr, depending on the initial temperature of the gas. Then once formed it will accrete onto the disk on timescale of the order, $t_{\text{dyn}}$, which ranges from 100 Myr to 1 Gyr as you vary $r$, the distance away from the galactic center. But this assumes no cloud disruption on its trip, so realistically the cloud will have to be destroyed and reformed in the inner halo if it is to reach the disk and fuel stars. Thus the time it takes for CGM gas to condense and reach the halo depends on $r$ and how the cloud is disrupted as it picks up speed. The cloud disruption through infall has been simulated frequently, e.g. (Heitsch & Putman 2009), (Armillotta et al. 2017). There is general consensus that bigger clouds are disrupted more slowly than smaller clouds. Armillotta et al. (2017) found that for large clouds, $R > 250$ pc, a large fraction of the cloud will survive longer than 250 Myr for cloud velocities $100-300 \text{ km s}^{-1}$. The next step should be to further quantify the rate at which gas is accreted onto the disk via CGM clouds under this formulation.
6 References

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