Mass, Morphing, Metallicities: The Evolution of Infalling High Velocity Clouds

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ABSTRACT

We revisit the reliability of metallicity estimates of high velocity clouds with the help of hydrodynamical simulations. We quantify the effect of accretion and viewing angle on metallicity estimates derived from absorption lines. Model parameters are chosen to provide strong lower limits on cloud contamination by ambient gas. Consistent with previous results, a cloud traveling through a stratified halo is contaminated by ambient material to the point that < 10% of its mass in neutral hydrogen consists of original cloud material. Contamination progresses nearly linearly with time, and it increases from head to tail. Therefore, metallicity estimates will depend on the evolutionary state of the cloud, and on position. While metallicities change with time by more than a factor of 10, well beyond observational uncertainties, most lines-of-sight range only within those uncertainties at any given time over all positions. Metallicity estimates vary with the cloud’s inclination angle within observational uncertainties. The cloud survives the infall through the halo because ambient gas continuously condenses and cools in the cloud’s wake and thus appears in the neutral phase. Therefore, the cloud observed at any fixed time is not a well-defined structure across time, since material gets constantly replaced. The thermal phases of the cloud are largely determined by the ambient pressure. Internal cloud dynamics evolve from drag gradients caused by shear instabilities, to complex patterns due to ram-pressure shielding, leading to a peloton effect, in which initially lagging gas can catch up to and even overtake the head of the cloud.

Key words: Galaxy:halo — Galaxy:evolution — hydrodynamics — turbulence — methods:numerical

1 BACKGROUND

The Galactic halo hosts a population of clouds whose line-of-sight velocities are inconsistent with Galactic rotation (Wakker & van Woerden 1997). Historically identified by their neutral gas component observed via HI 21 cm emission, their mass budget is actually dominated by ionized gas (Fox et al. 2004; Shull et al. 2009; Lehner & Howk 2011). These high velocity clouds (HVCs) range from large complexes of many degrees to structures at the resolution limit. Their diversity suggests different origins (Wakker & van Woerden 1997; Putman et al. 2012).

HVC metallicities may provide key information about cloud origins. Metallicities range between 10–50% solar (Wakker et al. 1999b; Fox et al. 2010; Shull et al. 2011; Richter et al. 2013; Collins et al. 2007; Richter 2017), possibly indicating satellite or circum-Galactic material as an origin. Intermediate and low velocity clouds (IVCs, LVCs) have higher metallicity, suggesting a Galactic wind source (Putman et al. 2012). Yet, mixing with or accretion of ambient material affects the reliability of metallicity constraints as indicators of HVC origin (Gritton et al. 2014; Kwak et al. 2015; Armillotta et al. 2016; Fox et al. 2016; Henley et al. 2017).

The contamination problem is one of turbulent mixing (Esquivel et al. 2006; Kwak & Shelton 2010). Yet, turbulent mixing is a challenging problem, especially in inviscid hydrodynamic simulations. Convergence is hard to reach, and mixing can be dominated by the numerical scheme (Shin et al. 2008; Goodson et al. 2017) and by the physics included in the modeling (Vietri et al. 1997; Viesser & Hensler 2007a; McCourt et al. 2015; Sander & Hensler 2021). More recently, the focus has shifted to contamination by accretion relying on cooling. A sizeable fraction of the HVC population may be Galactic fountain material (Fraternali et al. 2015; Marasco & Fraternali 2017, see also Putman et al. 2012). Gas launched from the disk generates a wake, leading to condensation of halo gas due to radiative losses (Gronke & Oh 2020, see also Heitsch & Putman 2009). Up to 100% of the original cloud mass may be accreted from the ambient gas (Gritton et al. 2017).

Best suited as a laboratory for HVCs are the Smith cloud (Smith 1963; Bland-Hawthorn et al. 1998; Lockman et al. 2008), and Complex C (Hulsbosch & Raimond 1966). Distances and orientations are well constrained (Wakker et al. 2003; Putman et al. 2003; Lockman et al. 2008 for the Smith Cloud; Wakker et al. 2007; Thom et al. 2008 for Complex C), to the point that trajectory reconstructions have been attempted (Nichols et al. 2014; Fraternali et al. 2015). Henley et al. (2017) compare their simulation results with the Smith Cloud, ex-
ploring different evolution times and viewing angles. They conclude that the probability to find "original" cloud material decreases with distance from the leading head of the cloud, and that therefore the origin of the Smith Cloud remains uncertain.

We revisit the contamination scenario, focusing on the probability to identify original cloud material in the neutral gas phase. Our analysis differs in four aspects from Henley et al. (2017); (1) Instead of a wind-tunnel experiment, the cloud is dropped in a Galactic gravitational potential; (2) The analysis of "original" cloud content is generalized to arbitrary viewing angles; (3) Column densities for metallicities are derived from line ratios, which in turn are determined by a Gaussian decomposition of the emission and absorption line profiles using ROSA (Marchal et al. 2019); (4) We allow the gas to cool below $10^4$ K. Radiative losses at $10^5$ K already lead to cooling-induced fragmentation (Shull & Moss 2020). Cooling below $10^4$ K can lead to the formation of cold neutral gas via thermal instability (Field 1965; Wolfire et al. 1995a,b), and thus can enhance overall fragmentation of the cloud (Tanner et al. 2016, for this effect on Galactic wind models).

We generated a set of hydrodynamic models of HVCs traveling through a diffuse halo medium (Sec. 2). We assess the probability to find cloud material at arbitrary positions (Sec. 3.2) and estimate the effects of contamination and viewing angle on abundance estimates (Sec. 3.4). We explore correlations between centroid velocities and metallicities (Sec. 3.5) and between column densities and metallicities (Sec. 3.6) as indicators for contamination. Caveats and consequences for observational estimates are mentioned in Sec. 4.

2 MODEL DESCRIPTION

We use a modified (App. A) version of Athena 4.2 (Stone et al. 2008), an Eulerian (fixed) grid code solving the equations of inviscid, compressible hydrodynamics in conservative form,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho C_e}{\partial t} + \nabla \cdot (\rho C_e \mathbf{u}) = 0$$

$$\frac{\partial \rho \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot ((E + P) \mathbf{u}) = \rho \mathbf{\nabla} \Phi$$

$$\frac{\partial E}{\partial t} + \nabla \cdot ((E + P) \mathbf{u}) = \rho \mathbf{\nabla} \Phi,$$

with the total mass density $\rho$, the gas velocity $\mathbf{u}$, the pressure $P$ and the total energy

$$E = \frac{1}{2} \rho u^2 + \frac{P}{\gamma - 1}.$$  

The "dye" for the cloud ($C_e$) [the halo ($C_h$)] is initialized to 1 wherever there is cloud [halo] material, and to 0 elsewhere. The adiabatic exponent is set to $\gamma = 5/3$, and the mean molecular weight to $\mu = 1$ in units of $m_H$. The latter choice affects cloud masses and sound speeds. Therefore, we will quote mass ratios, and any time-scales are approximations. The effective equation of state is determined by a combination of heating and cooling processes $\mathbf{\nabla}$ (App. A4) applied to the total energy equation (Eq. 6). We use the HLLC solver (Toro et al. 1994) in combination with a third-order Runge-Kutta integrator (App. A3).

2.1 Initial and Boundary Conditions

Not much is known about the "initial" shape and structure of HVCs, if such a concept is valid at all. A popular choice is to assume a spherical cloud with some density and temperature profile (e.g. Quilis & Moore 2001; Vieser & Hensler 2007a; Heitsch & Putman 2009; Gritton et al. 2014; Sander & Hensler 2021, but see Cooper et al. 2009, though in a different context), which is then exposed to a wind, or in our case, is falling through the Galactic halo. Such a setup emphasizes the cloud survival aspect of a HVC simulation. This is not surprising, since many previous studies using such initial conditions were interested in the survival of original cloud material.

We approach the choice of initial conditions differently, since uniform-density initial conditions can leave a clear imprint on the cloud structure for a substantial time (Henley et al. 2017). We do not aim at setting up a realistic cloud in the initial conditions, but we develop initial conditions that evolve into a realistic cloud, and take that cloud as our starting point for the analysis. The reader could think of this as a burn-in phase; the first half of the simulation (~140 Myr) is used to set up the cloud. During this phase, the cloud mostly preserves its initial structure and consists of original cloud material, with only minor contributions from ambient gas. Since we are considering an idealized numerical experiment investigating the contamination of a model cloud by ambient gas, it does not matter whether the cloud formed via stripping of gas from dwarf satellites (Nichols et al. 2011), via Galactic winds/outflows (Fraternali et al. 2015), or via any other scenario.

In this spirit, we imagine that the HVC starts its voyage at an initial distance of ~30 kpc above the plane, providing the cloud with sufficient room to lose any imprint of the initial conditions. We encase the cloud in a simulation domain such that it rests in the lower eighth of the box. The box measures $1 \times 1 \times 8$ kpc$^3$ with 256 cells along the short dimension. The box is three times as wide as the initial cloud diameter, which is resolved by 85 cells. This should suffice to capture the large-scale dynamics of the cloud in three dimensions (Pittard & Parkin 2016; Goodson et al. 2017). We set an initial cloud mass of $M_c = 5 \times 10^6$ M$_\odot$, comparable to that of Complex C (Thom et al. 2008, see also Warker et al. 2007) or depending on the distance estimate — the Smith Cloud (Bland-Hawthorn et al. 1998; Lockman et al. 2008). The latter authors arrive at a lower mass limit for H$_I$ of $10^6$ M$_\odot$ based on a comparison of several distance estimates placing the cloud at 12.4 ± 1.3 kpc. The cloud is chosen to be sufficiently massive so that some of its neutral gas survives the passage through the halo (Heitsch & Putman 2009). The initial, average cloud density is $n_H = 10$ cm$^{-3}$, or a factor of $10^2 \cdots 10^3$ higher than the average HVC density for Complex C (Thom et al. 2008; Shull et al. 2011). Once we start the analysis, peak cloud densities have dropped to ~1 cm$^{-3}$, with average densities of ~0.1 cm$^{-3}$.

The cloud itself is realized via a double top-hat density profile, with temperatures corresponding to the two-phase equilibrium temperatures (see Appendix A4 for details on the thermal physics). We identify neutral gas (HI) via the ionization fraction $x_I$ that is implicitly calculated as a function of total density $n_{tot}$ in our thermal physics description. Thus, the neutral column density is $N(HI) = \int n_{HI}(x) (1-x_I(x)) ds$ along a line of sight $s$. Initially at rest, the cloud does not have an ionized gas component, but this component will develop during the burn-in phase, reaching 50% of the total cloud mass.

A fixed gravitational potential accelerates the cloud toward the disk. The potential consists of a combination of dark matter halo, spheroidal bulge and disk potentials (Strickland & Stevens 2000; Cooper et al. 2008; Tanner et al. 2016). We assume a Galacto-centric
radius of 8.5 kpc, compared to 7.6 kpc for the Smith Cloud (Lockman et al. 2008). For simplicity regarding boundary conditions, we let the cloud drop perpendicularly to the Galactic plane. We do not assume a dark matter halo confining the cloud (Quilis & Moore 2001; Nichols & Bland-Hawthorn 2009; Galyart et al. 2016), nor do we include self-gravity (Sander & Hensler 2021).

We place the cloud in an initially isothermal, hydrostatically stratified halo determined by the gravitational potential, with $T = 2.2 \times 10^4$ K (Gupta et al. 2012; Miller & Bregman 2013, 2015). Henley & Shelton (2014) discuss the justification for non-isothermal models, at lower temperatures. Our choice of an isothermal model is motivated by numerical considerations of stability. Non-isothermal models are prone to convection (Henley & Shelton 2014), and in combination with lower assumed temperatures (Wang & Yao 2012) would require additional mechanical heating mechanisms such as galactic winds or cosmic rays (Girichidis et al. 2016) to achieve the appropriate scale heights. The required densities ($n \approx 10^{-4}$ cm$^{-3}$ at $z = 30$ kpc) in our model halo are low enough that the cooling time is longer than the typical crossing time through the simulation box, and therefore, the ambient gas temperature does not change drastically as long as the gas is not perturbed by the cloud’s passage. Lower halo temperatures would result in stronger cooling and thus in faster contamination of the cloud by ambient halo gas. We neglect any possible co-rotation of the warm halo gas with the Galactic disk (Qu et al. 2020). The cloud is initially in thermal pressure balance with the halo, at a pressure of $P/k_B = 660$ K cm$^{-3}$. We apply a grid of velocity perturbations drawn from a turbulent spectrum with index $|v|^2 k^{-4}$ on a wave number range $1/r_c \leq k \leq (2\Delta x)^{-1}$, where $r_c$ is the cloud radius. The specific choice of the turbulent spectrum does not affect the results. The velocity perturbations are normalized such that they generate a turbulent pressure $\rho c^2 P/k_B = 330$ K cm$^{-3}$, or 50% of the thermal pressure. The velocity perturbations break the initial symmetry of the setup, suppressing numerical artifacts typical for inviscid solvers in the presence of highly symmetric initial conditions. The kinetic energy from the turbulent motions make the cloud expand during the burn-in phase, pushing some cloud gas from the neutral into the ionized component (Sec. 3.2).

We assume solar metallicity ($Z/Z_\odot = 1$) for the cloud, and $Z/Z_\odot = 10^{-3}$ for the ambient gas. Miller & Bregman (2015) infer $Z/Z_\odot = 0.3$ for the halo, and metallicities for the Smith Cloud and Complex C are estimated at $Z/Z_\odot = 0.55 \pm 0.15$ (Fox et al. 2016) and $Z/Z_\odot = 0.1 - 0.3$ (Collins et al. 2007), respectively. Therefore, our choices are not motivated by observations, but rather by an attempt (a) to clearly distinguish between cloud and halo material, and (b) to provide strict lower limits for cloud contamination estimates. Choosing metallicities closer to observed values would make it harder to distinguish between cloud and halo material, and higher halo metallicities would lead to faster cooling and thus more accretion of halo gas entrained in the cloud’s wake. Taken together with the assumed halo temperature, our model cloud is therefore less likely to be contaminated than observed clouds. Even with these extreme choices, distinguishing between cloud and ambient material proves to be a challenge.

Cloud and halo gas are identified by passively advected scalar fields that can be imagined as a kind of dye being evolved together with the hydrodynamical equations (eqs. 2, 3). The cloud mass at any time is given by

$$M_c = \int \rho(x)C_c(x) \, d^3x,$$

with a color field $C_c$ that is initialized to 1 within the cloud and 0 otherwise. The gas density is given by $\rho = \mu m_H n$, where we set $\mu = 1$. Similarly, we identify original halo material, using a tracer field $C_h$.

Following Shin et al. (2008) and Goodson et al. (2017), we integrate the hydrodynamical equations within the rest frame of the cloud (App. A5), to improve the numerical accuracy. Since the cloud moves downward within the simulation box, the upper and lower boundary conditions in the vertical direction need to be modified. For the lower boundary condition, we calculate the hydrostatic density at the current vertical position of the boundary, and feed the corresponding hydrodynamic quantities to the boundary cells. The upper boundaries are set to ‘open if leaving’.

### 2.2 Data Analysis

Instead of post-processing, we have Athena generate position-velocity (PPV) cubes at 9 inclination angles from 10°···90° on the fly (App. A1). The cubes contain HI-21 cm and optically thin generic metal absorption line spectra at each position. The metallicities can change drastically within the cloud. An average metallicity can be derived by adding up column densities along the line of sight. To get a more accurate measure of the metallicity at each position, we mimic the observational procedure to estimate column densities for individual velocity components for both HI-21 cm and the generic metal tracer. We decompose all spectra (~ $6 \times 10^4$ spectra per time step, resulting in a total of ~ $4.5 \times 10^5$ spectra) into Gaussian components using ROHSA (Marchal et al. 2019, see App. B for details).

### 3 RESULTS

#### 3.1 Raw Data and Overall Evolution

The cloud passes through the stages typical for HVC simulations, from a flattened appearance (see Henley et al. 2017; Sander & Hensler 2021, for a demonstration) to an elongated head-tail structure. The cloud develops a diffuse, shock-compressed halo and a dense, small core. These are transients arising from the initial conditions, and they decay quickly to values consistent with the ambient pressure, leading to a more extended cloud that develops a tail (Fig. 1, top row). We skip those early stages in our analysis, since they are nearly completely determined by the choice of initial conditions (Cooper et al. 2009). Ram pressure decelerates the outer, more diffuse material, resulting in differential drag (Peek et al. 2007) and therefore in a centroid velocity gradient. The cloud begins to stretch out. Buoyancy effects in the stratified halo may start to play a role. At this point, a combination of radiative cooling and hydrodynamic instabilities fragments the cloud (Fig. 1, center row). The cloud hits the Galactic plane at $v_0 \sim 300$ km s$^{-1}$, close to the ballistic velocity, and in approximate agreement with the analytic estimates of Shull & Moss (2020). We discuss the amplitude of the impact velocity further in Sec. 4.1.4.

#### 3.1.1 Trajectories

Figure 2 compares the model cloud trajectory with that of test particle clouds, following the approach of Benjamin & Danly (1997, see their Fig. 3). We extend their discussion by considering mass accretion in addition to drag forces. The trajectories are calculated for three column densities ($10^{18}, 10^{19}, 10^{20}$ cm$^{-2}$), including drag (label ‘d’) and both drag and mass accretion (label ‘d+a’). The underlying equations
Figure 1. Integrated maps of the model cloud traveling through the halo toward the Galactic plane, at 200, 250, and 300 Myr (compare to Fig. 3). The cloud is viewed under an inclination angle of $\alpha_i = 50^\circ$. At $\alpha_i = 90^\circ$ the cloud moves toward the observer. Each map is accompanied by its profile along the vertical axis. The spatial extent is given in kpc on the map’s abscissa and the profile plot’s ordinate. Color bars show quantities indicated on the profile plot’s abscissa. From left to right: Neutral (HI) column density, centroid velocity (eq. [11]), total line width (eq. [10]), cloud mass fraction, and metallicity in terms of centroid velocity and position along the cloud’s long axis (see text). The first three quantities are calculated from the R08SA component fitting (Sec. B2) of HI-21 cm emission, and the last two quantities are based on the simulation raw data. At early times, column densities, centroid velocities, and metallicities show gradients, while at late times, the dynamics and hence the maps get more complex.
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3.1.2 Internal Dynamics and Peloton Effect

Figure 1 shows all quantities reconstructed from the R0HSA component fitting (Sec. B2) of HI-21 cm emission. The cloud is viewed under an inclination angle of $i_t = 60^\circ$. At earlier times (top row), column densities, centroid velocities, metallicities, and cloud mass fractions exhibit gradients. After 50 Myr (center row), the dynamics have turned more complicated and the distinct gradients (top row) have vanished. Of special interest is the structure of the centroid velocity, which starts developing inversions. Clumps of blue-shifted (faster) material appear over the whole length of the cloud. These inversions can also be seen in the associated vertical profiles. At early times, the fastest material is leading. Gas directly behind the cloud head is shielded from the ram pressure of the ambient medium (see also Forbes & Lin 2019). Radiative losses lead to condensation, so that the trailing gas contracts and – still shielded from ram pressure – can catch up to the leading head, eventually overtaking it. In other words, gas parcels within the cloud start to switch positions, not unlike in a peloton during bicycle races.

The line-of-sight velocity dispersion $\sigma_{\text{los}}$ (3rd column of Fig. 1) is generally smaller in the leading part of the cloud, indicating that these regions are less turbulent. This is consistent with some observations of HVCs (Brüns et al. 2001; Peek et al. 2007), as are the gradients in the centroid velocity. At later times, the cloud starts to heat up dynamically and gets more turbulent. We calculate $\sigma_{\text{los}}$ via the second moment of the position-position velocity cube,

$$\sigma_{\text{los}}^2 = \frac{\sum \Delta N(v_{\text{los}})(v_{\text{los}} - v_{\text{cen}})^2}{\sum \Delta N(v_{\text{los}})}$$

where the sum extends over all velocity channels $v_{\text{los}}, N(v_{\text{los}})$ is the column density for a given velocity channel, and $v_{\text{cen}}$ is the column-density-weighted centroid velocity

$$v_{\text{cen}} = \frac{\sum \Delta N(v_{\text{los}}) v_{\text{los}}}{\sum \Delta N(v_{\text{los}})}$$

Our calculation of $\sigma_{\text{los}}$ contains both thermal and non-thermal contributions to the dispersion. However, at the evolutionary stage of the cloud, the bulk of the gas resides more or less uniformly in the warm regime, around $T = 7 \times 10^{3}$ K (Fig. A1), corresponding to an isothermal sound speed of $\approx 8$ km s$^{-1}$. This is smaller than most dispersions shown in the third column of Figure 1, suggesting that gas dynamics, not gas temperatures, drive the variations in $\sigma_{\text{los}}$.

3.1.3 Metallicities and Contamination

The fourth column of Figure 1 shows the cloud mass fraction derived from the simulation data. The cloud mass fraction measures the
amount of original cloud material in the observed (neutral) cloud. At
early times, the cloud mass fraction indicates original cloud material
contaminated by entrained gas along the cloud (grey to orange tran-
sition in the cloud mass fraction). With increasing time (center and
bottom row), the cloud mass fraction drops, and the cloud consists
largely of accreted material. The cloud mass fraction in the center
row shows higher (green vs. orange) values at the outskirts close to
the leading head, corresponding to the red-shifted centroid velocities.
This is again the peloton effect at work, with originally leading ma-
terial (higher cloud mass fraction, green) being overtaken by newly
accreted material (lower cloud mass fraction, orange).

The fifth column relates the channel velocity \( v_{\text{los}} \) at each position
along the cloud’s long axis to the metallicity for each channel and
position. We generate a position-velocity plot showing the metallicity
of each position-velocity pair instead of the intensity. In other words,
each position along the long axis of the cloud is represented by a
spectrum where the brightness temperature has been replaced by
the channel’s metallicity. This information is usually not accessible
via observations unless high-resolution spectra are available for both
tracers, but it provides us with a detailed view of the correlation
between line-of-sight velocity and metallicity. The abscissa shows the
channel velocity over the same range as indicated by the colorbar in
the centroid velocity maps (2nd column). The ordinate shows, as in all
other panels, the position along the cloud’s long axis. Color indicates
the metallicity for each position and velocity channel. The position-
velocity map is derived from the full position-position-velocity cube
by integrating over the \( x \) (horizontal) axis. At early times (top row),
the position-velocity distribution shows a gradient from blue-shifted,
leading velocities, to red-shifted, trailing ones. The gradient indicates
that the “tail” of the cloud is red-shifted with respect to the head, and
therefore lagging behind the head. In the bottom panel, this gradient
has vanished, but metallicities are generally lower at higher velocity
for all positions, suggesting contamination. Ambient material at low
metallicity is entrained all along the cloud, but it lags behind the main
body of the cloud, and therefore travels at more positive (red-shifted)
line-of-sight velocities.

Since most of the cloud material gets replaced by ambient gas, the
earlier statement about heating of cloud material should not be taken
literally. The velocity dispersion increases mostly because ambient
material is entrained in the cloud’s wake, then cools and later appears
as neutral gas (Gronke & Oh 2020). Actual heating of original cloud
material plays only a minor role. While the cloud appears to be heated
dynamically, this is just an effect of coherently moving cloud material
being replaced by more turbulent ambient material.

3.2 Probability for Cloud Material

The probability for neutral gas to be cloud material \( P(\text{cloud}\mid \text{HI}) \)
allows us to assess whether metallicities can constrain cloud origin
scenarios. If \( z \) is the coordinate along the cloud’s long axis, also taken
as the local tangent to the trajectory, the probabilities are calculated
by determining the ratio of the tracer fields in terms of a mixing
parameter averaged laterally over all positions at a fixed \( z \).

\[
P(\text{cloud}\mid \text{HI}, z) = \frac{1}{2} \left[ 1 + \frac{\tilde{C}_c(z) - \tilde{C}_h(z)}{\tilde{C}_c(z) + \tilde{C}_h(z)} \right]
\]

where the subscript \( c, h \) denote cloud and halo material, respectively.
The average color field \( \tilde{C}_c(z) \) is defined as

\[
\tilde{C}_c(z) = \frac{\int p(x) C_c(x)(1 - s_c(x)) \, dx \, dy}{\int p(x)(1 - s_c(x)) \, dx \, dy}.
\]

where \( x \) and \( y \) are the lateral axes, i.e. perpendicular to the trajectory.

The local gas density is given by \( \rho \), and the ionization fraction is
\( x_I(x) \). The probability \( P(\text{cloud}\mid \text{HI}, z) \) is normalized to 1 for each \( z \).

Figure 3 summarizes the time evolution of the probability to find
cloud material along the long axis of the cloud (panels [a,b]). Initially,
the neutral gas component (panel [c,d]) consists of 100% cloud ma-
terial, but the probabilities decrease once a tail forms around 100 Myr.
The cloud ends up mostly consisting of accreted material. Probabili-
ties < 1 indicate that ambient material transitioned to the neutral
phase via cooling (compare panels [a,c,d]). Its spread along the tra-
jectory (panel [b]) suggests that this material is entrained in the wake
of the cloud, consistent with the metallicity and cloud mass fraction
maps of Figure 1. Figure 3e shows the mass of gas at temperatures
\( \leq 10^3, 10^3, 10^2 \) K, as a measure of the cold gas component. At
the end of the burn-in phase, the cold neutral component drops to less
than a percent of the neutral cloud mass because of the initial over-
pressure within the cloud (§ 2.1). Once the cloud hits the plane at
\( t \approx 240 \) Myr, the neutral component grows again, via accretion.

Figure 4 provides a simplified view of the distribution of accreted
mass. We split the cloud into a lower third (the ‘head’ – dashed lines)
and the remaining two thirds (the ‘tail’ - solid lines). The inversion
between head and tail in the total HI gas indicates that initially, the
head is heated by compression (dip in mass fraction around 20 Myr)
and then starts to cool again. Meanwhile, the tail loses most of its
neutral gas. At around 100 Myr, the total HI-mass (blue) rises above
the cloud HI-mass (orange), a trend that is amplified until the end,
when ~ 90% of the tail’s neutral gas consist of accreted gas. Gained
HI (green) supports this interpretation, since it converges on the total
HI mass. The mass fraction for the head show a similar evolution,
except that they stay a factor of ~ 30 below the tail mass fractions at
late times. Therefore, most of the gas is accreted in the tail, consistent
with Henley et al. (2017). The mass ratios demonstrate that for our
evolved cloud, only 10% of the neutral gas is original cloud material.
See also Secs. 3.4 and 4.2.

We restrict the subsequent analysis to the time range between
140 and 240 Myr, when the cloud has evolved away from its initial
conditions, but has not yet crossed the disk’s mid-plane.

3.3 Thermal Evolution

The neutral gas mass drops again after the cloud punches through
the disk (Fig. 3e), suggesting that the ambient thermal pressure may
be the driver for the overall mass evolution. Figure 5 takes a closer
look at the thermal state of all gas in the simulation domain. Pressure
(Fig. 5a), temperature (5b) and density (5c) distributions in terms of
mass fractions are shown against simulation time. Red lines indicate
ambient halo values for pressure and density. The bulk of the ambient
gas stays at the isothermal halo temperature of \( 2.2 \times 10^6 \) K, because
of the long cooling time. Grey lines in the temperature (Fig. 5b) and
density (Fig. 5c) history show the thermal equilibrium value derived
from the cooling curve (Fig. A1) at the current ambient pressure.
At the higher pressures around vertical distances of \( z = 0 \) (Galactic
plane), two equilibrium solutions are possible , one for warm (solid)
and one for cold gas (dashed). The red and grey lines stand for
reference values taken at the cloud’s center of mass.

The pressure distribution (Fig. 5a) is constrained by the ambient
gas pressure for the most part. Ram pressure drives the cloud gas
above the red line, and cloud gas in the wake will be at lower press-
ure (blue regions below the red line). Approaching the plane, the
pressure increases overall. Once the cloud punches through the disk,
the ambient pressure begins to drop, and the leading (faster) cloud
Figure 3. (a) Probability to detect original, neutral cloud gas (eq. 12) as a function of position along the cloud’s major axis and model evolution time. The probability drops to less than 10% at times \( t > 250 \) Myr. (b) Same as (a), but along the cloud’s trajectory. (c) Average HI column density along the cloud’s long axis, similar to (a). The column density increases toward late times, indicating accretion. (d) HI column density split into contribution from original cloud (purple) and accreted halo (green/blue) material. (e) Mass history for HI at temperatures \( T < 10^4 \) K, \( T < 10^3 \) K and \( T < 10^2 \) K, measuring the gas mass in the warm and cold neutral component. Subsequent analysis is limited to \( 140 < t < 240 \) Myr, after the cloud has lost the imprint of the initial conditions, and before it hits the Galactic plane.

Figure 4. Time evolution of mass fractions over the whole cloud extent (solid) and the leading third (head) of the cloud. Mass fractions refer to the current cloud mass. The cloud tail accretes a factor \( \sim 30 \) more material than the head. The cloud ends up with \( \sim 10\% \) of original cloud material, both in head and tail.

The dense, cold cloud gas of the initial conditions is nearly gone at the end of the burn-in phase (around 140 Myr), leaving only warm gas at \( T \sim 10^4 \) K. Since the temperatures in the three thermal regimes (hot, warm, cold) are mostly constant, the densities (Fig. 5c) follow a shape similar to the pressure (Fig. 5a). At around 100 Myr, mass starts to flow from the hot component at \( T = 2.2 \times 10^6 \) K to the warm gas. Once the cloud approaches the plane, the pressure increases such that density and temperature can access the two thermal equilibrium solutions. The warm phase (\( \sim 10^4 \) K) tries to transit to the cold phase, but dynamics prevent a full conversion, so that it reaches only the unstable neutral phase (Murray et al. 2018). The onset of the transition can be seen around 150 Myr and 200 Myr (Fig. 5b), with gas moving from \( T = 10^5 \) K to lower temperatures. While the pressure at \( P/k_B > 3 \times 10^5 \) K cm\(^{-3}\) should suffice for warm and cold neutral gas to co-exist at the same pressure (compare to Fig. A1), dynamical heating competes with radiative cooling (Gazol et al. 2001, though in a different context), suppressing the full formation of a cold phase.

Most of the cloud’s thermal state and thus the presence of neutral gas is determined by the ambient pressure (Wolfire et al. 1995b), while dynamical effects lead to a gradual transition between the stable phases. Yet, conversion from warm to cold neutral medium is not complete by any means, rather, any gas leaving the warm neutral phase cools down only to the unstable neutral phase.

3.4 Time Evolution and Inclination Angle

Figure 6 shows the time evolution between 140 and 240 Myr (see Fig. 3) of the cloud profiles in dependence of inclination angles, from \( \alpha_i = 10^\circ \) (nearly in the plane of sky) to \( \alpha_i = 90^\circ \) (cloud moving toward observer). Quantities and color schemes are identical to those used in Figure 1.

The cloud stretches out and develops a head-tail structure, which...
then breaks up into fragments moving at different speeds as indicated by the blue-shifted material throughout the cloud for larger $\alpha_1$ (centroid velocities, 2nd column). Metallicities and cloud mass fractions drop with time, indicating contamination of the cloud by ambient material. Original cloud material is indicated by grey tones (cloud mass fraction, 5th column), while ambient gas is shown in blue tones. At a given time, the cloud mass fraction decreases from head (bottom) to tail (top) for all angles but $90^\circ$. Therefore, the tail is contaminated faster than the head, suggesting contamination via accretion into the cloud wake rather than by sweep-up of material by the head. Despite the peloton effect and accretion, finding original cloud material near the leading part of the cloud is more likely than toward the trailing part, consistent with the results of Henley et al. (2017). The cloud is predominantly contaminated by entraining ambient material in its wake, and not via sweepup and compression. If sweepup and compression of ambient material were the main accretion mechanism, the leading part of the cloud should contain relatively less original cloud material than the trailing part. Gritton et al. (2017) point out that for supersonic motions, condensation at the head of the cloud can be suppressed because a bow shock develops, but that material still can condense in the wake. At $\sim 300$ km s$^{-1}$ (Fig. 2), the cloud travels supersonically with respect to the background medium.

Histograms of characteristic cloud measures (Figure 7) highlight how accretion affects the overall cloud properties. The average column density increases with time, while the average metallicity and cloud mass fraction drop by more than a factor of 10. The width of both metallicity and cloud mass fraction distributions decrease with time for larger inclination angles. The cloud accretes ambient material, replacing the original cloud material, and thus resulting in a more homogeneous composition. For $\alpha = 10^\circ$, the metallicity distribution develops a tail toward lower values, resulting in a spread of over 1.5 dex. For small inclination angles, more material at low column densities contributes to the lines-of-sight. Since low column densities are more likely to arise from accreted material (Sec. 3.6), (for our model parameters) lower metallicities indicating ambient gas.

The cloud decelerates once it has punched through the disk. This reduces the drag along the cloud, and thus the velocity differences of accreted material between different cloud locations. Therefore, the overall velocity dispersion drops, and the cloud becomes dynamically more coherent.

Only extreme inclination angles ($\alpha_1 = 10^\circ, 90^\circ$) affect the overall appearance of the cloud (Fig. 6). For small inclination angles, relative velocities along the cloud trajectory are suppressed, and therefore, the peloton effect cannot be observed. Metallicity estimates and distributions are consistent except for fully head-on trajectories ($\alpha_1 = 90^\circ$). Because of the large aspect ratio of cloud length over width, only $\alpha_1 = 90^\circ$ leads to confusion in metallicities. Variations in metallicities and cloud mass fraction along the cloud’s long axis are consistent except for $\alpha_1 \approx 90^\circ$.

The probability to find original cloud material decreases from head to tail (Fig. 6 last column showing the cloud mass fraction), and it strongly depends on position, time and inclination angle. Note that finding original cloud material is related, but not identical to finding sight-lines with high original cloud material content. The difference can be seen by comparing the cloud mass fractions in Figs. 1 and Fig. 6. Small pockets of sight-lines with $\sim 50\%$ cloud material survive, yet their area coverage is vanishingly small compared to the cloud area (See also Sec. 3.6).

Distributions (Fig. 7) are differently affected by inclination angles. Column densities generally increase for higher $\alpha_1$, but their distribution narrows, while the centroid velocities show the reverse effect, since for low $\alpha_1$, the lag of cloud material along the trajectory does not contribute to the velocity spread. At larger inclination angles, at least two centroid velocity components are discernible. Linewidths also increase with increasing $\alpha_1$, as more gas is mixed along the line-of-sight, leading to velocity crowding. Metallicities and cloud mass fraction distributions are mostly unaffected by the viewing angle, suggesting that the latter two – especially metallicities in terms of observables – are robust against variation in $\alpha_1$.

### 3.5 Velocity Lags and Metallicity

Our discussion suggests that lower cloud mass fractions and ambient (in our case, lower) metallicities should be correlated with larger velocity lags along the cloud. Figure 8 confirms this expectation for early times. The 2D histograms of cloud mass fraction (top) against centroid velocity display a distinct negative gradient from small ($\bar{v}_{cen} = 0$) to large lags ($\bar{v}_{cen} > 0$). Metallicities (bot-
3.6 Column Densities and Metallicities

Due to its proximity, the HVC complex with probably the highest number of abundance measurements is Complex C (Wakker et al. 1999b; Richter et al. 2001; Tripp et al. 2003; Collins et al. 2003, 2007; Shull et al. 2011). Collins et al. (2007) explore correlations between [O/H] abundances and HI column densities as a signature of mixing with ambient gas, hypothesizing that higher column densities should show less contamination with ambient material. While present, the observed trend is weak due to measurement uncertainties. The fourth column of Fig. 1 provides a modeler’s version of Fig. 8 of Collins et al. (2007). In the center row, the cloud mass fraction at the cloud edge (around $y = 0$) is lower than that of the cloud’s main body. These regions coincide with lower column densities (1st column). Note that while Collins et al. (2007) would expect an anti-correlation between metallicity and column density, for our model parameters a positive correlation between column density and metallicity indicates mixing between ambient and cloud gas.

Figure 9 provides a more detailed view, showing the joint distributions of cloud mass fraction as a proxy for metallicity, and column density. We show the cloud mass fraction, since the metallicities are model-dependent. A positive correlation between cloud mass fraction and column density indicates mixing and accretion. Indeed, for the first two time instances (top and center row), all viewing angles suggest a positive trend. When the cloud is about to punch through the disk, column densities rapidly increase, and a substantial amount

Figure 6. Laterally averaged profiles along the cloud’s long axis, against time after burn-in (140 Myr), for four inclination angles. Quantities shown and color schemes are identical to those in Fig. 1. The ordinate shows the position along the cloud’s long axis, in units of the simulation domain’s lateral extent. From left to right: Column density, centroid velocity, non-thermal line-width, metallicity, and cloud mass fraction. Grey tones in the cloud mass fraction indicate highest fraction of original material. Therefore, material is accreted predominantly in the tail (top), and not in the head (bottom) of the cloud. All inclination angles except $\alpha_i = 90^\circ$ (head-on) show a gradient in metallicity and cloud mass fraction.
of ambient material is accreted. This leads to a flat distribution with cloud mass fraction – most of the neutral gas is now stemming from the ambient medium.

The specific choice of cloud and halo metallicities in our model precludes quantitative predictions of metallicities within any given cloud. Yet, the metallicity gradient (Fig. 6) across a cloud provides an opportunity to distinguish between enrichment or dilution of cloud material, which will occur when the cloud’s metallicity is lower or higher than that of the ambient gas, respectively. In the case of enrichment, the metallicity gradient along the cloud should be positive, since material of higher metallicity gets successively entrained in the cloud’s wake (Fig. 4). In the case of dilution (as in our model cloud), the metallicity gradient should be negative, as low-metallicity gas gets entrained. While specific values will depend on several factors including the metallicity contrast between the cloud and the ambient gas, estimating the metallicity gradient across a given cloud even by two or three sight lines may provide information about the relative metallicities.

The Smith Cloud can serve as an example. Although three metallicity measurements for the Smith Cloud (Fox et al. 2016) do not show a clear gradient, the two sight-lines close to the head of the cloud show higher values ([S/H] = −0.09 ± 0.33 and −0.14 ± 0.13), while the cloud tail has a lower value of [S/H] = −0.58 ± 0.20. If we group the first two values together, the above reasoning would lead us to conclude that the Smith Cloud’s material has been diluted (not enriched) by ambient gas of lower metallicity. On the other hand, Henley et al. (2017) focus on the two higher metallicity estimates and conclude that their models are consistent with the Smith Cloud having been enriched over time by high-metallicity ambient gas, but this does not explain the lower metallicity measured in the cloud wake. More observational metallicity constraints, in both the cool clouds and the hot ambient gas, are needed for further progress.

Fig. 9 provides a measure for the probability to find sight-lines with high original cloud material content, at a given point in the cloud’s evolution. While the overall cloud mass fraction drops with time, pockets of sight-lines with a high cloud mass fraction survive (center row, lower inclination angles). Yet their area coverage is small compared to that of accreted material. For example the probability to find sight-lines with \( f_{cl} > 0.5 \) at \( \Delta t = 80 \) Myr is less than 1%.

4 DISCUSSION

We presented an analysis of a hydrodynamical simulation of a gas cloud traveling through the Galactic halo, determining the probability to find original cloud material within the observed cloud at any given time and viewing angle. The model assumes cloud formation via infall, possibly due to stripping from dwarf satellites. Other origin scenarios for cloud formation have been discussed elsewhere (e.g. Ji et al. 2018, for in-situ formation).
Figure 8. Time history (columns) of the cloud mass fraction $f_c$ (top) and metallicity log $Z$ (bottom) as function of the centroid velocity ($x$-axis), for several inclination angles (rows). Times $\Delta t$ are given after burn-in ($140$ Myr). Cloud mass fractions systematically drop with higher (red-shifted) velocities, and with increasing time. For the metallicities, both statements are generally true, though the viewing angles can hide the signature. Color scales of marginalized histograms are identical to those of Fig. 1.

4.1 Caveats

4.1.1 Missing Physics

We leave out the effects of thermal conduction and magnetic fields. Brüggen & Scannapieco (2016) investigated the role of heat conduction with 3D adaptive mesh refinement models, concluding that electron thermal conduction does play a role in the evaporation of clouds of low column densities. Though applied to a different scenario, namely the acceleration of cold clouds in a galactic wind, the underlying physics is similar. Two-dimensional models of cloud disruption including radiative cooling and heat conduction (Vieser & Hensler 2007a,b; Armillotta et al. 2017) have shown that heat conduction can help to stabilize the cloud against disruption. The latter authors exploit the advantages of reduced dimensions and explore a range of cloud radii and masses. Kooij et al. (2021) demonstrate numerically that magnetic fields might suppress thermal conduction (Spitzer 1962) and thus help cool gas "survive". Yet they point out that thermal conduction – even if suppressed – still affects the evolution of a cloud.

In a similar study of cloud acceleration in hot winds, McCourt et al. (2015) conclude that, when using tangled magnetic fields, the clouds start to move with the background medium in near pressure equilibrium, rather than being disrupted. The magnetic field suppresses the dynamical instabilities (see also Grønnow et al. 2017) while it links the cloud to the ambient gas via sweep-up of field lines, thus increasing the drag force above hydrodynamic values. To capture the effect of magnetic fields fully, three-dimensional simulations are necessary (Grønnow et al. 2018), since in two dimensions, interchange modes cannot develop (Stone & Gardiner 2007). Still, magnetic fields seem capable of suppressing some of the condensation of ambient material into the wake (Grønnow et al. 2018, see also Field 1965 for the suppression of thermal instability in the presence of magnetic fields), therefore we expect that including magnetic fields in our models would slow down the cloud and suppress cloud disruption, resulting in less mass lost and therefore in a higher probability to detect cloud material along the tail (Fig. 3).
Figure 9. 2D histograms of cloud mass fraction against column density, to test for correlation between metallicity and column density. A positive correlation indicates mixing between cloud and ambient gas. Colors stand for the number of sight lines. Times are $\Delta t = 60, 80, 100$ Myr (top to bottom). Different viewing angles are arranged horizontally, from in-the-plane (left) to a head-on view (right).

4.1.2 Metallicities and Disk Structure

Our choice of initial cloud and specifically halo metallicities will reduce the condensation of halo gas in the wake of the cloud compared to more realistic (higher) halo metallicities. Therefore, our contamination estimates are lower limits, since higher halo metallicities would lead to more gas condensing in the wake of the cloud via cooling. Also, metallicity gradients would be less steep than found in our analysis. Omitting the thin disk with its colder and denser (neutral) gas component in our simplified halo model also suppresses accretion of ambient gas.

4.1.3 Beam Smearing

We assume pencil beams for both absorption and emission. All HVC metallicity estimates are derived by combining HI 21 cm measurements taken at a finite beam width with UV metal-line measurements taken at an infinitesimal beam (pencil) width and are therefore sensitive to beam-smearing effects, in which small-scale (sub-beam) structure in the radio data could impact the actual HI column along the UV pencil beam. Wakker et al. (1999a, 2001) quantified this effect for a few lines-of-sight, extending to a list of HI 21 cm columns for all available HVC sight lines (Wakker et al. 2011). They estimated that, typically, HI columns are accurate within 10 – 25%, or ±0.04 – 0.10 in log $N_H$. We will leave the consideration of beam-smearing effects for a future contribution.

4.1.4 Impact Velocity

The cloud’s velocity relative to the ambient gas is not only relevant for hydrodynamical considerations since instabilities can be suppressed for supersonic motions (Chandrasekhar 1961) and therefore the accretion mechanism changes (Gritton et al. 2017), but it also could serve as a check against observations. Yet, three-dimensional velocity information for HVCs is available only under rare circumstances. Lockman et al. (2008) determine the three spatial velocity components of the Smith Cloud, with a total space velocity of $V_{tot} = 300$ km s$^{-1}$ and a vertical component of 73 ± 26 km s$^{-1}$ at which the cloud is approaching the disk. Its orbit is highly inclined and prograde, so that the Smith cloud’s velocity relative to the ambient gas would expected to be much less than $V_{tot}$. Heitsch et al. (2016) proposed a method to reconstruct the three-dimensional cloud propagation direction required to calculate $V_{tot}$, based on the cloud morphology in the position-velocity plane and $v_{LSR}$. Applying the method to a subset of clouds identified in HIPASS (Putman et al. 2002), they estimate $V_{tot}$ of up to 300 km s$^{-1}$ for a few clouds. Yet, these estimates, and the resulting relative speed with respect to the ambient gas, strongly depend on the assumed halo gas rotation model.

Theoretical estimates of the infall velocity depend strongly on the cloud’s starting point, on the gravitational potential, and on whether drag is included. Shall & Moss (2020) find infall velocities of ~350 km s$^{-1}$ without drag and a logarithmic potential (Fig. 2), while
Benjamin & Danly (1997) including drag estimate terminal velocities of \( \sim 150 \text{ km s}^{-1} \). Self-consistent models in which the cloud is dropped in a stratified halo (Heitsch & Putman 2009; Sander & Hensler 2021) reach cloud velocities between 150 and > 300 km s\(^{-1}\). Wind-tunnel experiments explore ranges of 100–350 km s\(^{-1}\) (e.g. Kwak et al. 2011).

### 4.2 Consequences for Observations

1. The peloton effect (Sec. 3.1.2) could be detected in three ways:
   (a) High-resolution (interferometry) observations at the leading head of a cloud would exhibit "unordered" velocity fields not following a systematic velocity gradient from head to tail (Fig. 6).
   (b) The (thermally) cooler head would show a large non-thermal component. This could be looked for in H\(_\text{I}\) 21 cm data as well as in UV absorption lines (Fig. 6).
   (c) Joint distributions of metallicity and centroid velocities would show double or multiple peaks (Fig. 8).

2. Using metallicities as diagnostics for cloud origin is complicated mostly by substantial contamination especially of the trailing cloud parts due to accretion of ambient gas (Figs. 3, 4, 6, see also Henley et al. 2017). Though the leading cloud part is less prone to accrete material specifically at supersonic motions, the peloton effect will eventually also lead to contamination, flattening the metallicity gradient to a point where distinguishing between original and accreted gas might be impossible.

3. Not only does the mass fraction of original cloud material drop with time, but also the area coverage of sight-lines with high original cloud mass fraction decreases rapidly. The probability to find such sight-lines strongly depends on inclination angle and time (Figs. 1 and 6). Fig. 9 suggests that the probability to find sight-lines with \( f_{cl} > 0.5 \) is vanishingly small for evolved clouds. Therefore, in all likelihood, metallicity measurements in HVCs will not represent original cloud properties, but metallicity gradients will provide insight about cloud contamination.

4. While the H\(_\text{I}\) column densities vary over nearly two orders of magnitude at any time, the metallicities are spread over a half a dex at most at any given time (Fig. 7). Metallicity drop with time due to accretion well beyond observational uncertainties (Fox et al. 2016), yet an individual snapshot shows a largely uniform metallicity. The spread is larger than observational uncertainties at any given time, allowing observational distinction between cloud and ambient material only if their metallicities differ sufficiently. Viewing angles do not affect the metallicity estimates.

5. If the ambient metallicity is known, variations of the metallicity along the cloud can provide information about whether gas has been mostly accreted via compression at the leading head or via condensation in the trailing tail.

6. Metallicity gradients along the cloud trajectory can provide insight about the relative metallicities of cloud and ambient gas, based on the observation that ambient material is successively entrained in the cloud’s wake (Fig. 6, Sec. 3.6).

7. Correlations between metallicity and column density can indicate the presence of cloud gas mixing with ambient gas (Collins et al. 2007). Figure 9 suggests that such a correlation would strongly depend on the evolutionary state of the cloud – if such a concept is applicable at all. A “pristine” cloud traveling through the halo would show a correlation between metallicity and column density, but once the majority of a cloud’s mass is actually coming from the ambient gas, the correlation between metallicity and column density should be flat.

### 4.3 Outlook

While our parameter choices do allow us to set strong lower limits on contamination, ultimately, exploring a range of halo and cloud metallicities, cloud masses, and trajectories might seem advisable to further constrain how accretion affects realistic clouds. Yet, based on our parameter choices, we do not expect results to change qualitatively.

Our model addresses the evolution and contamination of an infalling cloud, but similar contamination mechanisms might be expected for outflowing clouds driven by Galactic winds (e.g. Di Teodoro et al. 2018; Lockman et al. 2020). Depending on the balance between ram pressure acceleration by the wind and gravitational acceleration, corresponding models might be closer to wind-tunnel experiments than envisaged here.

### 5 CONCLUSIONS

We use hydrodynamic simulations of infalling high-velocity clouds run with a modified version of Athena (Stone et al. 2008) to probe how reliably metallicity measurements can identify 'original' cloud material over time, along the cloud, and under a range of viewing angles. The model parameters are chosen to provide conservative (strong) limits on cloud contamination by ambient material. Our analysis has led us to conclude:

1. The cloud is contaminated nearly linearly with time, until most of the original cloud material has been replaced by accreted gas (Fig. 7). The cloud is well defined at any fixed time, but not across time, and thus is not defined by constancy in its constituent gas particles, but by self-propagating density and pressure perturbations. The energy necessary to reform the cloud is provided by the potential energy of the over-densities.

2. Our super-sonically moving cloud is to some extent contaminated at its leading edge by sweep-up, but mostly along the cloud tail, due to thermal condensation into the wake of the cloud (Fig. 6). The thermal state of cloud gas - whether original or accreted - is largely controlled by the ambient pressure (Fig. 5) and the cloud dynamics.

3. The cloud dynamics can get extremely complex, with initially lagging material that is shielded from ram pressure catching up to the head, and even passing the head, of the cloud (peloton effect). This would affect centroid velocity gradients and thus drag estimates (Peek et al. 2007), and it could also introduce uncertainties in metallicity gradients.

4. While the dynamical quantities (centroid velocity and velocity dispersion) depend on the inclination angle, the overall metallicities are unaffected by inclination within observational uncertainties, due to identification of individual velocity components (Fig. 7). Only for small inclination angles (i.e. clouds mostly in the plane of sky), accreted material at low column densities will display metallicities (given our model parameters) lower by more than 1 dex compared to the bulk of the cloud.

5. The correlation between metallicities and column densities along a range of sight lines not only indicates mixing (Collins et al. 2007), but also could indicate the evolutionary stage of the cloud.
APPENDIX A: MODIFICATIONS TO ATHENA

The code is available at FH’s github repository. The initialization file can be found under src/prob/heitsch/hvc.c.

A1 PPV Cubes

Because of the high resolution requirements, we implemented an on-the-fly analysis, including the calculation of position-position-velocity (PPV) cubes for selected viewing angles. All lines-of-sight can be calculated at initialization of the simulation. The block decomposition used in the parallelization requires that each processor dumps its version of a rotated PPV cube. These are then added and stitched together in a post-processing step. This approach limits the radiative transfer to optically thin emission and/or background absorption. Self-absorption cannot be modeled. We calculate spectra via brightness temperature can be converted into a total column density as the integral along the line of sight for two species.

The HI-21 cm emission is determined for each velocity channel \( v \) as the integral along the line of sight \( s \),

\[
T_H(v) = c_{HI}^{-1} \int n(s) \phi(v - v(s)) \, ds, \tag{A1}
\]

where \( n(s) \) is the local density in \( \text{cm}^{-3} \) along the line-of-sight for gas with \( T < 10^4 \) K, and the function

\[
\phi(v - v(s)) = \frac{1}{\sqrt{\pi} \Delta v_{th}(s)} \exp\left( -\frac{(v - v(s))^2}{\Delta v_{th}(s)} \right) \tag{A2}
\]

describes the thermal broadening with the local thermal width \( \Delta v_{th}(s) = \sqrt{2 k_B T(s)}/m_{HI} \), where \( m_{HI} \) is the hydrogen atom mass, and \( k_B \) the Boltzmann constant. The constant \( c_{HI} = 1.823 \times 10^{18} \text{cm}^{-2} \left( \text{K km s}^{-1} \right)^{-1} \). Each channel is \( \Delta v = 1 \text{ km s}^{-1} \) wide. The brightness temperature can be converted into a total column density via

\[
N(\text{HI}) = c_{HI} \int T_H(v) \, dv. \tag{A3}
\]

The absorption by a tracer species (for example singly ionized sulfur, SII, Fox et al. 2016) is calculated based on the local metallicity,

\[
Z = Z_c C_c + Z_h C_h, \tag{A4}
\]

where the subscripts \( c/h \) denote cloud/halo material, and with the sum of the color fields identifying cloud and halo material, \( C_c + C_h = 1 \). The color field for the cloud \( C_c \) is defined via equation 7. We write the absorption coefficient as

\[
\kappa(s) = \sigma_{\text{SII}} Z(s) n(s), \tag{A5}
\]

assuming \( \sigma_{\text{SII}} = 10^{-22} \text{ cm}^2 \) as a cross section for the tracer. The exact choice is irrelevant for our purposes, and is solely motivated by rendering the resulting absorption line as optically thin, i.e. the optical depth at a given velocity channel \( v \) is given by

\[
\tau(v) = \int \kappa(s) \phi(v - v(s)) \, ds. \tag{A6}
\]

The column density per channel \( N(v) \) can then be calculated as \( \tau(v)/\sigma_{\text{SII}} \). We note that we use the same mean molecular weight for HI and the tracer species. Further, we neglect any issues arising from varying ionization degrees (Fox et al. 2016). In that sense, our ‘metal absorber’ is just a generic quantity, providing the simplest possible model. The closest equivalent to observational measurements would be metallicity estimates via OI/HI coupled via charge exchange (Collins et al. 2003).

A2 Internal Energy

The Athena stock version applies density and pressure floors after the reconstruction step as a safeguard to prevent negative densities and/or pressures in extreme flow situations. For problems involving radiative losses, the floor values can lead to unreasonably high heating rates, leading to point-wise “explosions”. Therefore, we implemented an internal energy integration following Bryan et al. (2014). Details are discussed by Goodson et al. (2016) and Frazer & Heitsch (2019).

A3 Time Stepping

To increase the stability of the code in the presence of strong temperature gradients and high-Mach number shocks, we implemented a time-variation-diminishing third-order Runge-Kutta integrator (Gottlieb & Shu 1998) in Athena. While slower than the CTU and VL integrators of the Athena 4.2 stock version, the benefit of improved stability while being able to run at Courant numbers of 0.5 seemed a reasonable trade-off. The RK3 architecture has the advantage that arbitrary source terms can be included with ease at third order in time, i.e. at the same order as the hydrodynamical fluxes. This is especially of advantage in the case of energy source terms such as cooling (App. A4) or co-moving grids (App. A5). Despite the higher time-accuracy, extreme flow situations, specifically in the presence of radiative losses, can occasionally lead to negative densities. In such cases, the integrator repeats the failed step at half the Courant timestep for the whole grid.

A4 Thermal Physics

Heating and radiative losses are implemented as a look-up table in five variables, namely the gas density \( n \), the temperature \( T \), the distance from the Galactic plane \( z \) to account for reduction of soft UV radiation density, the column density \( N \) to account for UV and x-ray shielding, and the metallicity \( Z \). Tables were generated with Mappings-V (Sutherland & Dopita 1993). The \( z \)-dependence of the radiation field follows Wolfire et al. (1995b). Figure A1 shows the thermal equilibrium pressures \( P \), temperatures \( T \), and ionization degrees against gas density \( n \), in dependence of metallicity (left), distance above the plane (center), and shielding column (right). Metallicity and shielding can strongly affect the thermal behavior of the gas (Wolfire et al. 1995b). The calculation of the ionization degree assumes collisional ionization equilibrium, since we are interested only in the overall dynamics rather than the details of the turbulent mixing layers or the ionization stages of various ions (Kwak & Shelton 2010; Gnat et al. 2010). We use the ionization degree to determine the fraction of neutral gas during the analysis step. Note that a detailed treatment of the thermal physics across ‘phase transitions’ (e.g. Stone & Zweibel 2009) including non-equilibrium cooling can change the nature of the transition and thus could eventually affect the efficiency of ambient gas condensation in the cloud wake (Gnat 2017).

Heating and cooling are implemented as sources \( \dot{E}_{\text{cool}} \) to the total energy equation,

\[
\partial_t E + \nabla \cdot (\mathbf{u} (E + P)) = \dot{E}_{\text{cool}}. \tag{A7}
\]

To prevent over-shoots once thermal equilibrium is reached, and to avoid negative temperatures, we sub-cycle on the cooling using an adaptive stepsize Runge-Kutta-Fehlberg integrator, solving

\[
\frac{dT}{dt} = f(n, T, N, Z, z). \tag{A8}
\]

The RKF integrator subcycles on eq. (A8) until a full Courant
timestep $\Delta t$ is reached. The resulting energy difference $\Delta E$ is used to calculate

$$E_{\text{cool}} = \frac{\Delta E}{\Delta t}. \quad \text{(A9)}$$

### A5 Comoving Grid

There are two advantages to have the simulation domain track the cloud. First, we can limit the simulation domain to a box around the cloud. This allows us to track the cloud for an arbitrary amount of time, as long as we provide the correct (time- and position-dependent) boundary conditions. Gritton et al. (2014) and Galyardt & Shelton (2016) decided to solve this problem by using adaptive mesh refinement in a domain spanning the whole trajectory of the cloud, refining only on the position of the cloud. Yet, since we are mostly interested in turbulent mixing, we decided to insist on a uniform spatial resolution. Shin et al. (2008) point out the second advantage, namely that a comoving grid can be realized by subtracting the center-of-mass velocity from the box, thus reducing the effect of truncation errors in the cloud dynamics. We follow their approach, adjusting the subtracted velocity such that the leading cloud edge is kept at a (nearly) constant position within the box (see also Goodson et al. 2017). The comoving grid is implemented as a change in position and velocity applied to the grid coordinates, updated together with the fluid variables. Thus, the grid positions are updated together with the RK3 integration. The RK3 integrator takes care of resetting the coordinates also, in case a timestep needs to be repeated (see Appendix A3).
APPENDIX B: ROHSA

Fitting the spectra to determine column densities and thus abundances met with two challenges. First, a single position-position-velocity cube can contain thousands of usable lines-of-sight, since we are not limited to background sources for absorption spectra. Second, a single line-of-sight may contain multiple velocity components, the number of which is not known in advance. The first challenge mandates a fast and efficient fitting mechanism, and the second challenge requires the fitting procedure to allow for an arbitrary number of Gaussian components, yet ideally without over-fitting the data. A first attempt to use Gaussian Mixture Models (Reynolds 2015) turned out to be unviable because of time requirements. We therefore decided to use a modified version of ROHSA (Marchal et al. 2019) that decomposes jointly the emission and absorption position-position-velocity cubes described in Appendix A1 into multiple velocity components using a Gaussian model.

B1 Model

The data are the measured brightness temperature $T_b(v, r)$ and optical depth $\tau(v, r)$ at a given projected velocity $v$. The proposed model $\hat{T}_b(v, \theta_{em}(r))$ and $\hat{\tau}(v, \theta_{tau}(r))$ are a sum of $N$ Gaussian $G(v, \theta_n(r))$

$$\hat{T}_b(v, \theta_{em}(r)) = \sum_{n=1}^{N} G(v, \theta_{n}^{em}(r)), \quad (B1)$$

$$\hat{\tau}(v, \theta_{tau}(r)) = \sum_{n=1}^{N} G(v, \theta_{n}^{tau}(r)), \quad (B2)$$

with $\theta_{em}(r) = (\theta_{1}^{em}(r), \ldots, \theta_{n}^{em}(r))$, $\theta_{tau}(r) = (\theta_{1}^{tau}(r), \ldots, \theta_{n}^{tau}(r))$, and where

$$G(v, \theta_n(r)) = a_n(r) \exp\left(-\frac{(v - \mu_n(r))^2}{2\sigma_n(r)}\right) \quad (B3)$$

is parametrized by $\theta_n = (a_n, \mu_n, \sigma_n)$ with $a_n \geq 0$ being the amplitude, $\mu_n$ the position, and $\sigma_n$ the standard deviation 2D maps of the $n$-th Gaussian profile. The residuals are

$$L_{em}(v, \theta_{em}(r)) = \hat{T}_b(v, \theta_{em}(r)) - T_b(v, r), \quad (B4)$$

and

$$L_{tau}(v, \theta_{tau}(r)) = \hat{\tau}(v, \theta_{tau}(r)) - \tau(v, r). \quad (B5)$$

The estimated parameters $\hat{\theta}_{em}$ and $\hat{\theta}_{tau}$ are defined as the minimizer of a cost function that includes the sum of the squares of the residuals,

$$Q(\theta_{em}, \theta_{tau}) = \frac{1}{2} \lambda_{em} \left\| L_{em}(v, \theta_{em}) \right\|_2^2 + \frac{1}{2} \lambda_{tau} \left\| L_{tau}(v, \theta_{tau}) \right\|_2^2. \quad (B6)$$

where $\lambda_{em}$ and $\lambda_{tau}$ are hyper-parameters than tune the balance between the emission and absorption terms. Although the two terms in Eq. B6 are combined in a single cost function, the parameters $\theta_{em}$ and $\theta_{tau}$ are independent and the estimated parameters obtained using any arbitrary optimization algorithm would lead to the same result as if they were evaluated separately. However, such a combination allows us to add regularization terms as priors on the model parameters $\theta_{em}$ and $\theta_{tau}$.

Following Marchal et al. (2019), each parameter map of $\theta_{em}(r)$ and $\theta_{tau}(r)$ is filtered using a Laplacian kernel to ensure that the solution is spatial coherent. In other words, adjacent pixels are forced to have a similar Gaussian decomposition. The following regularization term, itself containing energy terms, is added to the cost function given in Eq. (B6)

$$R(\theta_{em}, \theta_{tau}) = \frac{1}{2} \sum_{n=1}^{N} \lambda_{a_n}^{em} \left\| D a_n^{em} \right\|_2^2 + \lambda_{\mu_n}^{em} \left\| D \mu_n^{em} \right\|_2^2 \quad (B7)$$

$$+ \lambda_{a_n}^{tau} \left\| D a_n^{tau} \right\|_2^2 \quad (B8)$$

$$+ \frac{1}{2} \sum_{n=1}^{N} \lambda_{\mu_n}^{tau} \left\| D \mu_n^{tau} \right\|_2^2 \quad (B9)$$

$$+ \lambda_{\sigma_n}^{tau} \left\| D \sigma_n^{tau} \right\|_2^2, \quad (B10)$$

where $D$ is the matrix perform the 2D convolution (see Marchal et al. (2019) for complementary details), and $\lambda_{a_n}^{em}, \lambda_{\mu_n}^{em}, \lambda_{\sigma_n}^{em}, \lambda_{a_n}^{tau}, \lambda_{\mu_n}^{tau}, \lambda_{\sigma_n}^{tau}$ are hyper-parameters than tune the balance between the different terms.

In addition, we also add the following regularization term to the cost function given in Eq. (B6)

$$R'(\theta_{em}, \theta_{tau}) = \frac{1}{2} \sum_{n=1}^{N} \lambda_{\mu_n}^{em} \left\| \mu_n^{em} / \mu_n - 1 \right\|_2^2 + \lambda_{\sigma_n}^{em} \left\| \sigma_n^{em} / \sigma_n - 1 \right\|_2^2. \quad (B11)$$

where $\lambda_{\mu_n}$ and $\lambda_{\sigma_n}$ are hyper-parameters than tune the balance between the different terms. These energy terms aim to maximize the correlation of the velocity fields and dispersion velocity fields between emission and absorption. In other words, these energy terms ensure that each Gaussian pair describing a component seen in absorption and emission has a similar velocity and a similar velocity dispersion.

The full cost function is then

$$J(\theta_{em}, \theta_{tau}) = Q(\theta_{em}, \theta_{tau}) + R(\theta_{em}, \theta_{tau}) + R'(\theta_{em}, \theta_{tau}), \quad (B12)$$

and the minimizer is

$$[\hat{\theta}_{em}, \hat{\theta}_{tau}] = \arg\min_{\theta_{em}, \theta_{tau}} J(\theta_{em}, \theta_{tau}), \quad (B13)$$

wrt. $a_n^{em} \geq 0, a_n^{tau} \geq 0 \ \forall \ n \in [1, \ldots, N]$. Following Marchal et al. (2019), this optimization relies on L-BFGS-B (for Limited-memory Broyden–Fletcher–Goldfarb–Shanno with Bounds), a quasi-Newton iterative algorithm described by Zhu et al. (1997) which allows for the positivity constraints of the amplitudes to be taken into account.

The initialization of the optimization is carried out in two steps. First, the optical depth model $\theta_{tau}$ is adjusted using the second term in Eq. B6. For this step, we use the multi-resolution process from coarse to fine grid described in Marchal et al. (2019). Then the solution $\theta_{tau}$ is used to initialize $\theta_{em}$. Finally, the full cost function given in Eq. B12 is used to perform the final optimization and to update $\theta_{em}$ and $\theta_{tau}$, ensuring a spatially coherent solution with a correlated velocity field and velocity dispersion field for each Gaussian component.

The decomposition is performed using ROHSA hyper-parameters $N = 6$, and $\lambda_{em} = \lambda_{tau} = \Lambda_{a_n}^{em} = \Lambda_{\mu_n}^{em} = \Lambda_{\sigma_n}^{em} = \Lambda_{a_n}^{tau} = \Lambda_{\mu_n}^{tau} = \Lambda_{\sigma_n}^{tau} = 1$. The number of Gaussian $N$ is chosen to ensure that the signal is fully encoded. Note that due to regularisation, this does not imply that six Gaussians are used along each line of sight (Marchal et al. 2019).

B2 Estimating physical parameters

The spatially coherent parameters $\hat{\theta}_{em}, \hat{\theta}_{tau}$ obtained with ROHSA allows us to extract the mean physical properties of the HVC gas along each line of sight.
The column density map is

\[ N(\text{HI})(r) = C a_n^m(r) a_{n}^m(r). \]  

(B14)

All the following quantities (metallicity, centroid velocity, and total velocity dispersion, see also eqs. [11] and [10]) are weighted by the column density,

\[ \bar{Z}(r) = \frac{\sum_{n=1}^{N} N(\text{HI})_n(r) (a_n^m(r) / a_{n}^m(r))}{\sum_{n=1}^{N} N(\text{HI})_n(r)}, \]  

(B15)

\[ v_c = \frac{\sum_{n} v T_{b}^{n}(r)}{\sum_{n} T_{b}^{n}(r)}, \]  

(B16)

\[ \sigma^2(r) = \frac{\sum_{n} (v - v_c(r))^2 T_{b}^{n}(r)}{\sum_{n} T_{b}^{n}(r)}. \]  

(B17)

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DATA AVAILABILITY STATEMENT

Raw and reduced simulation data are available on request.

REFERENCES

Armillotta L., Fraternali F., Marinacci F., 2016, MNRAS, 462, 4157
Armillotta L., Fraternali F., Werk J. K., Prochaska J. X., Marinacci F., 2017, MNRAS, 470, 114
Benjamin R. A., Danly L., 1997, ApJ, 481, 764
Bland-Hawthorn J., Veilleux S., Cecil G. N., Putman M. E., Gibson B. K., Maloney P. R., 1998, MNRAS, 299, 611
Brüggen M., Scannapieco E., 2016, ApJ, 822, 31
Bryan G. L., et al., 2014, ApJS, 228, 11
Chandrasekhar S., 1961, Hydrodynamic and hydromagnetic stability. International Series of Monographs on Physics, Oxford: Clarendon
Collins J. A., Shull J. M., Giroux M. L., 2003, ApJ, 585, 336
Collins J. A., Shull J. M., Giroux M. L., 2007, ApJ, 657, 271
Cooper J. L., Bicknell G. V., Sutherland R. S., Bland-Hawthorn J., 2008, ApJ, 674, 157
Cooper J. L., Bicknell G. V., Sutherland R. S., Bland-Hawthorn J., 2009, ApJ, 703, 330
Cox D. P., 2005, ARA&A, 43, 337
Di Teodoro E. M., McClure-Griffiths N. M., Lockman F. J., Denbo S. R., Endsley R., Ford H. A., Harrington K., 2018, ApJ, 855, 33
Esquivel A., Benjamin R. A., Lazarian A., Cho J., Leitner S. N., 2006, ApJ, 648, 1043
Ferrière K. M., 2001, Reviews of Modern Physics, 73, 1031
Field G. B., 1965, ApJ, 142, 531
Forbes J. C., Lin D. N. C., 2019, AJ, 158, 124
Fox A. J., Savage B. D., Wakker B. P., Richter P., Sembach K. R., Tripp T. M., 2004, ApJ, 602, 738
Fox A. J., Wakker B. P., Smoker J. V., Richter P., Savage B. D., Sembach K. R., 2010, ApJ, 718, 1046
Fox A. J., et al., 2016, ApJ, 816, L11
Fraternali F., Marasco A., Armillotta L., Marinacci F., 2015, MNRAS, 447, L70
Frazier C. C., Heitsch F., 2019, MNRAS, 489, 52
Galyardt J., Shelton R. L., 2016, ApJ, 816, L18
Gazol A., Vázquez-Semadeni E., Sánchez-Salcedo F. J., Scalo J., 2001, ApJ, 557, L121
Girichidis P., et al., 2016, ApJ, 816, L19
Gnat O., 2017, ApJS, 228, 11
Gnat O., Sternberg A., McKee C. F., 2010, ApJ, 718, 1315
Goodson M. D., Luebbers I., Heitsch F., Frazier C. C., 2016, MNRAS, 462, 2777
Goodson M. D., Heitsch F., Eklund K., Williams V. A., 2017, MNRAS, 468, 3184
Gottlieb S., Shu C. W., 1998, Mathematics of Computation, 67, 73
Gritton J. A., Shelton R. L., Kwak K., 2014, ApJ, 795, 99
Gritton J. A., Shelton R. L., Galyardt J. E., 2017, ApJ, 842, 102
Gronek, M. O. S., 2020, MNRAS, 492, 1970
Grssonow A., Tepper-García T., Bland-Hawthorn J., McClure-Griffiths N. M., 2017, ApJ, 845, 69
Grssonow A., Tepper-García T., Bland-Hawthorn J., 2018, ApJ, 865, 64
Gupta A., Mathur S., Krongold Y., Nicastro F., Galeazzi M., 2012, ApJ, 756, L8
Heitsch F., Putman M. E., 2009, ApJ, 698, 1485
Heitsch F., Bartell B., Clark S. E., Peek J. E. G., Cheng D., Putman M., 2016, MNRAS, 462, L46
Henley D. B., Shelton R. L., 2014, ApJ, 784, 54
Henley D. B., Gritton J. A., Shelton R. L., 2017, ApJ, 837, 82
Hulsbosch A. N. M., Raimond E., 1966, Bull. Astron. Inst. Netherlands, 18, 413
Ji S., Oh S. P., McCourt M. S., 2018, MNRAS, 476, 852
Kooij R., Grönnow A., Fraternali F., 2021, MNRAS, 502, 1263
Kwak K., Shelton R. L., 2010, ApJ, 719, 523
Kwak K., Henley D. B., Shelton R. L., 2011, ApJ, 739, 30
Kwak K., Shelton R. L., Henley D. B., 2015, ApJ, 812, 111
Lehner N., Howk J. C., 2011, Science, 334, 955
Lockman F. J., Benjamin R. A., Heroux A. J., Langston G. I., 2008, ApJ, 679, L21
Lockman F. J., Di Teodoro E. M., McClure-Griffiths N. M., 2020, ApJ, 888, 51
Marasco A., Fraternali F., 2017, MNRAS, 464, L100
Marchal A., Miville-Deschênes M.-A., Orieux F., Gac N., Soussen C., Lesot M.-J., d’Allonnes A. R., Salome Q., 2019, A&A, 626, A101
Marinacci F., Binney J., Fraternali F., Nipoti C., Ciotti L., Londrillo P., 2010, MNRAS, 404, 1464
McCourt M., O’Leary R. M., Madigan A.-M., Quataert E., 2015, MNRAS, 449, 2
Miller J. M., Bregman J. N., 2013, ApJ, 770, 118
Miller J. M., Bregman J. N., 2015, ApJ, 800, 14
Murray C. E., Stanimirović S., Goss W. M., Heiles C., Babler B., Kim C.-G., 2018, ApJS, 238, 14
Nichols M., Colless J., Colless M., Bland-Hawthorn J., 2011, ApJ, 703, 527
Nichols M., et al., 2014, ApJ, 795, 99
Nichols M., Bland-Hawthorn J., 2009, ApJ, 707, 1642
Nicholson P. A., 1965, The Theory of Stellar Interiors. National Series of Monographs on Physics, Oxford: Clarendon
QuZ., Bregman J. N., Hodges-Kluck E., Li J.-T., Lindley R., 2020, ApJ, 894, L21
Reynolds D., 2015, in Jain S. Z. L., A. K., ed., Encyclopedia of Biometrics. Springer US, p. 827, doi:10.1007/978-1-4899-7488-4_196, https://doi.org/10.1007/978-1-4899-7488-4_196

MNRAS 000, 1–18 (2018)
Heitsch et al.

Richter P., 2017, Gas Accretion onto the Milky Way. p. 15, doi:10.1007/978-3-319-52512-9_2
Richter P., Sembach K. R., Wakker B. P., Savage B. D., Tripp T. M., Murphy E. M., Kalberla P. M. W., Jenkins E. B., 2001, ApJ, 559, 318
Richter P., Fox A. J., Wakker B. P., Lehner N., Howk J. C., Bland-Hawthorn J., Ben Bekhti N., Fechner C., 2013, ApJ, 772, 111
Sander B., Hensler G., 2021, MNRAS, 501, 5330
Shin M., Stone J. M., Snyder G. F., 2008, ApJ, 680, 336
Shull J. M., Moss J. A., 2020, ApJ, 903, 101
Shull J. M., Jones J. R., Danforth C. W., Collins J. A., 2009, ApJ, 699, 754
Shull J. M., Stevans M., Danforth C., Penton S. V., Lockman F. J., Arav N., 2011, ApJ, 739, 105
Shull J. M., Danforth C. W., Anderson K. L., 2021, ApJ, 911, 55
Smith G. P., 1963, Bull. Astron. Inst. Netherlands, 17, 203
Spitzer L., 1962, Physics of Fully Ionized Gases
Stone J. M., Gardiner T., 2007, ApJ, 671, 1726
Stone J. M., Zweibel E. G., 2009, ApJ, 696, 233
Stone J. M., Gardiner T. A., Teuben P., Hawley J. F., Simon J. B., 2008, ApJS, 178, 137
Strickland D. K., Stevens I. R., 2000, MNRAS, 314, 511
Sutherland R. S., Dopita M. A., 1993, ApJS, 88, 253
Tanner R., Cecil G., Heitsch F., 2016, ApJ, 821, 7
Thom C., Peek J. E. G., Putman M. E., Heiles C., Peek K. M. G., Wilhelm R., 2008, ApJ, 684, 364
Toro E. F., Spruce M., Speares W., 1994, Shock Waves, 4, 25
Tripp T. M., et al., 2003, AJ, 125, 3122
Vieser W., Hensler G., 2007a, A&A, 472, 141
Vieser W., Hensler G., 2007b, A&A, 475, 251
Vietri M., Ferrara A., Miniati F., 1997, ApJ, 483, 262
Wakker B. P., van Woerden H., 1997, ARA&A, 35, 217
Wakker B. P., Savage B. D., Oosterloo T. A., Putman M. E., 1999a, in Gibson B. K., Putman M. E., eds, Astronomical Society of the Pacific Conference Series Vol. 166, Stromlo Workshop on High-Velocity Clouds. p. 302
Wakker B. P., et al., 1999b, Nature, 402, 388
Wakker B. P., Kalberla P. M. W., van Woerden H., de Boer K. S., Putman M. E., 2001, ApJS, 136, 537
Wakker B. P., et al., 2003, ApJS, 146, 1
Wakker B. P., et al., 2007, ApJ, 670, L113
Wakker B. P., Lockman F. J., Brown J. M., 2011, ApJ, 728, 159
Wang Q., Yao Y., 2012, arXiv e-prints, p. arXiv:1211.4834
Wolfire M. G., Hollenbach D., McKee C. F., Tielens A. G. G. M., Bakes E. L. O., 1995a, ApJ, 443, 152
Wolfire M. G., McKee C. F., Hollenbach D., Tielens A. G. G. M., 1995b, ApJ, 453, 673
Zhu C., Byrd R. H., Lu P., Nocedal J., 1997, ACM Trans. Math. Softw., 23, 550

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