Is Multiphase Gas Cloudy or Misty?

Max Gronke* and S. Peng Oh

Department of Physics, University of California, Santa Barbara, CA 93106, USA

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ABSTRACT
Cold $T \sim 10^4$K gas morphology could span a spectrum ranging from large discrete clouds to a fine ‘mist’ in a hot medium. This has myriad implications, including dynamics and survival, radiative transfer, and resolution requirements for cosmological simulations. Here, we use 3D hydrodynamic simulations to study the pressure-driven fragmentation of cooling gas. This is a complex, multi-stage process, with an initial Rayleigh-Taylor unstable contraction phase which seeds perturbations, followed by a rapid, violent expansion leading to the dispersion of small cold gas ‘droplets’ in the vicinity of the gas cloud. Finally, due to turbulent motions, and cooling, these droplets may coagulate. Our results show that a gas cloud ‘shatters’ if it is sufficiently perturbed out of pressure balance ($\delta P/P \sim 1$), and has a large final overdensity $\chi_f \gtrsim 300$, with only a weak dependence on the cloud size. Otherwise, the droplets reassemble back into larger pieces. We discuss our results in the context of thermal instability, and clouds embedded in a shock heated environment.

Key words: galaxies: evolution – hydrodynamics – ISM: clouds – ISM: structure – galaxy: halo – galaxy: kinematics and dynamics

1 INTRODUCTION

Understanding the formation and dynamics of cold ($\sim 10^4$K) gas is a crucial facet of galaxy formation. Cold gas not only fuels star formation, but (in contrast to the hot phase) it is detectable up to high redshift, and thus widely used as a probe of galactic outflows or the circumgalactic medium (e.g., Veilleux et al. 2005; Tumlinson et al. 2017). However, despite its importance and ubiquity, cold gas around galaxies remains an enigma. It is present in galactic halos for a wide range of galaxy masses (e.g., Steidel et al. 2010; Wisotzki et al. 2016), but its origin, perhaps from thermal instability or ejection from the galaxy, is poorly understood. Such cold gas should be vulnerable to disruption by hydrodynamic instabilities (Klein et al. 1994; Zhang et al. 2017). Furthermore, it has been established observationally through multiple probes that circumgalactic cold gas can be structured on both small scales ($< 100$ pc, and potentially substantially less; e.g., Rauch et al. 1999; Churchill et al. 2003; Schaye et al. 2007; Hennawi et al. 2015), and large scales ($\sim 100$ kpc; e.g., Werk et al. 2014). The origin, survival, and morphology of cold gas are all outstanding puzzles.

What could set a characteristic scale for cold gas? McCourt et al. (2018, henceforth: M18) showed that when the cooling time falls far below the sound-crossing time in a cooling cloud, it becomes strongly underpressured relative to surrounding hot gas, and ‘shatters’ to cloudlets of size $\ell_{\text{shatter}} \sim \min(c_{\text{cool}}) \sim 0.1$ pc $(n/\text{cm}^{-3})^{-1}$, akin to gravitational fragmentation to the Jeans length. Significant observational evidence for this picture is reviewed in M18. Sparre et al. (2019) and Liang & Remming (2019) subsequently investigated 3D hydro and 2D MHD shattering in a wind-tunnel like setup respectively. Thus, ‘clouds’ of cold, atomic gas may have the structure of a mist, composed of tiny fragments dispersed throughout the ambient medium.

On the other hand, in Gronke & Oh (2018, 2019), where we revisited the problem of cloud entrainment in a wind, we found that cold gas could survive hydrodynamic instabilities only if clouds exceed a critical length-scale $r_{\text{min}} > c_{\text{cool}, \text{mix}} \gg \ell_{\text{shatter}}$. This criterion arises from $t_{\text{cool}, \text{mix}} < t_{\text{cr}}$, where $t_{\text{cool}, \text{mix}}$ is the cooling time of the mixed warm gas and $t_{\text{cr}}$ is the cloud-crushing time. In this regime, the cooling of mixed, ‘warm’ gas causes the cold cloud mass to grow. The cloud retains its monolithic identity; cold gas only survives as large ‘clouds’. The mass growth rate is similar in nearly static simulations with weak shear. In both cases, the cloud pulsates due to loss of pressure balance seeded by radiative cooling, entraining hot gas which subsequently cools.

The ‘misty’ and ‘cloudy’ scenarios may appear mutually contradictory. However, terrestrially, we experience both; in the ISM and CGM, there is observational evidence for both. What is not known is the physical conditions under which cold gas should exist primarily in a ‘misty’ or ‘cloudy’ state, which we address here. This question has important consequences for the survival and dynamics of cold gas, the...
2 Numerical Setup

‘Shattering’ appears to take place when a large \( \chi / \ell_{\text{shatter}} \) cloud falls out of pressure balance with its surroundings. This occurs in at least two physical situations: (i) thermal instability, when the cloud pressure falls precipitously due to radiative cooling; (ii) a shock engulfing cold clouds, when the surrounding gas pressure rises sharply.

To simulate this, we placed four spherical clouds with radius and overdensity \( \chi_c \) inside the simulation domain of size \( 8r_{\text{cell}} \) per dimension. We placed one cloud in center of the simulation domain, but displaced the three others with a maximum offset per dimension of \( r_{\text{cell}} \) (see inset in Fig. 1 for initial conditions). The deviation from spherical symmetry avoids the curvuncle instability (Moschetta et al. 2001), which seeds grid-aligned artifacts. We varied \( \chi_c \) between 1.01 and 1000; the lower (higher) values mimic thermal instability and cold gas embedded in a shock heated environment respectively. Furthermore, we perturb the density in every cell by a random factor \( r \) which is drawn from a Gaussian with \( (\mu, \sigma) = (1, 0.01) \) (truncated at 3\( \sigma \)).

We set the initial cloud temperature to be \( T_{\text{c,ini}} = T_{\text{floor}} \), where the cooling floor is \( T_{\text{cool}} = 4 \times 10^4 \text{K} \) and \( T_{\text{cool}} / T_{\text{floor}} \) varies from 1.5 to 1000. The cloud is initialized to be in pressure balance with its surroundings, but rapidly falls out of pressure balance via radiative cooling. Since the cooling time is much shorter than the sound crossing time, the cloud cools isochorically to \( T_{\text{cool}} \) and \( P_{\text{cool}} / P_{\text{hot}} \approx T_{\text{cool}} / T_{\text{c,ini}} < 1.0 \). Thus, varying \( T_{\text{cool}} / T_{\text{floor}} \) is equivalent to varying the degree of initial pressure imbalance; we tested this explicitly. The cloud can only regain pressure balance at a higher overdensity \( \chi = \chi_c T_{\text{c,ini}} / T_{\text{floor}} \). We define \( \ell_{\text{shatter}} \equiv c_{\text{cool}} T_{\text{floor}} / c_{\text{cool}}(\rho_T, T_{\text{floor}}) \).

To emulate heating of the background hot gas, we inhibited cooling for \( T > 0.67T_{\text{cool}} \). We performed most of our simulations using \( r_{\text{cell}} / \ell_{\text{cell}} = 16 \) cell elements but we increased the resolution to \( r_{\text{cell}} / \ell_{\text{cell}} = 64 \) for some runs as indicated in the text. Note that we do not resolve \( \ell_{\text{shatter}} \) in our simulations; shattering proceeds down to grid scale. While the morphology of ‘shattered’ gas is not numerically converged, we have explicitly checked that our conclusions about the presence/absence of shattering (the focus of this paper) is numerically robust to resolution. We find that the resolution requirements to observe shattering are less stringent in 3D than in the 2D simulations of M18.

The simulations were run using Athena 4.0 (Stone et al. 2008) using the HLLC Riemann solver, second-order reconstruction with slope limiters in the primitive variables, and the van Leer unsplit integrator (Gardiner & Stone 2008), and the Townsend (2009) cooling algorithm (using a 7-piece power-law fit to the Sutherland & Dopita (1993) solar metallicity cooling function). The runtime of the simulations was max \( (10t_{\text{shatter}}, 10t_{\text{c,final}}, 10t_{\text{cool,final}}) \), or until the cloud clearly shattered, with a significant number of droplets leaving the simulation domain. Animations visualizing our numerical results are available at http://max.lyman-alpha.com/shattering.
Figure 3. The resolution-adjusted maximum number of clumps identified during the runtime of a simulation, as a function of cloud size when sonic contact is lost (see text) and final overdensity $\chi$. The number of clumps is shown a sharp transition at $\chi_{\text{crit}}$ for ‘shattering’ given by the dashed line (see text for details). The marker shape indicates the initial overdensity $\chi_i$. Points might be slightly offset for visualization.

3 RESULTS

Our simulations have 3 variables: cloud size, degree of pressure imbalance, and initial overdensity $\chi_i$. The number of clumps is shown a sharp transition at $\chi_{\text{crit}}$ for ‘shattering’ given by the dashed line (see text for details). The marker shape indicates the initial overdensity $\chi_i$. Points might be slightly offset for visualization.

What is the effect of the initial overdensity $\chi_i$? We first vary the parameters $(\chi_i, T_{\text{cl}}/T_{\text{floor}})$, holding cloud size $r_{\text{cl}} \gg \ell_{\text{shatter}}$ roughly constant. Fig. 2 shows the simulations which did and did not shatter, with triangles pointing downwards and upwards, respectively. A less overdense cloud needs to be more out of pressure balance (higher $T_{\text{cl}}/T_{\text{floor}}$) to shatter. The boundary between these regimes has a scaling $T_{\text{cl}}/T_{\text{floor}} \propto \chi_i^{-1}$, collapsing the criterion to a single parameter: the final overdensity must exceed a critical value $\chi_{\text{f}} \sim (T_{\text{cl}}/T_{\text{floor}}) \chi_i > \chi_{\text{crit}} \sim 300$. This requirement flattens out at large $\chi_i > \chi_{\text{crit}}$: at least $T_{\text{cl}}/T_{\text{floor}} \gtrsim 2$ (corresponding to $P_{\text{cl}} \lesssim 0.5P_{\text{floor}}$) is required.

The case of lower initial overdensities ($\chi_i \lesssim 10$) requires special care. Since the initial cooling time is long at low densities, the cloud may initially retain sonic contact, that is $r_{\text{cl}} \lesssim c_{\text{cool}}(T_{\text{cl}}, \rho_{\text{cl}})$. However, since $t_{\text{cool}}$ plumets as it cools and contracts, it will lose sonic contact at some point (since $r_{\text{cl}} \gg \ell_{\text{shatter}} \equiv c_{\text{u, floor}} t_{\text{cool}}(T_{\text{floor}}, P_{\text{floor}})$). The scale important for shattering is in fact the radius the cloud has when it loses sonic contact, which is $r_{\text{cl}} = \sqrt{\gamma P_0 / \rho_0 t_{\text{cool}}(P_0 / \rho_0, \rho)}$ where $P_0$ is the ambient pressure and $\rho_0 = \rho_0(r_i / r_*)^3$ comes from mass conservation. We use $r_{\text{cl}}$ to evaluate cloud size. If the cloud loses sonic contact before contraction (or never does), we set $r_{\text{cl}}^{*1}$ to $r_{\text{cl}}$.

Can shattering occur during thermal instability of background hot gas? This has not been shown to date; M18 began with non-linear initial conditions, $\chi_i \sim 10$. We simulated linear initial overdensities $\chi_i = 1.01$ and $T_{\text{cl}}/T_{\text{floor}} = \{10^3, 10^5\}$, where there is a long period of slow contraction. Here, we did not set the cooling function to zero above some temperature but instead introduced constant volumetric heating, set to equal the total cooling rate at each timestep. The cloud shatters, or does not, for $\chi_i \sim \{10^3, 10^4\}$ respectively (see unfilled triangles in Fig. 2), as expected since these bracket $\chi_{\text{crit}} \approx 300$.

Since $(T_{\text{cl}}/T_{\text{floor}}, \chi_i)$ collapse to the single variable $\chi_i$, the entire parameter space can be viewed in the $(\chi_i, r_{\text{cl}}/\ell_{\text{shatter}})$ plane. In Fig. 3 we show how these two variables affect the maximum number of clumps which appear during the simulation. Larger clouds require higher resolution; the larger initial size $\chi_i \sim \{2, 10\}$ cases are run with $r_{\text{cl}}/\ell_{\text{shatter}} = 64$ and only the $\chi_i \sim 100$ runs use the fiducial resolution of $r_{\text{cl}}/\ell_{\text{shatter}} = 16$. To take this into account, we display the rescaled variable $N_{\text{clumps,max}} = N_{\text{clumps}} r_{\text{cl}}/\ell_{\text{shatter}}/64$. The distribution of maximum clump sizes is shown a sharp transition at $\chi_{\text{crit}} \approx 300 \left(\chi_{\text{f}}/\ell_{\text{shatter}}\right)^{1/6}$ shown by the dashed line in Fig. 3. We caution that the simulations of large clouds may not be fully converged, so the exact scaling exponent may change. However, the conclusion that $\chi_{\text{crit}}$ scales only weakly with cloud size is robust.

What is the physical origin of shattering? We can gain insight by studying simulations which straddle the $\chi_{\text{crit}}$ boundary. Fig. 4 shows snapshots of two simulations, both with $\chi_i \sim 10$ and $r_{\text{cl}} \sim 5 \times 10^6 \ell_{\text{shatter}}$ but differing $T_{\text{cl}}/T_{\text{floor}}$, such that $\chi_i \sim 200$ and $\sim 400$ (upper and lower row, respectively). The clouds evolve as follows: (i) initially, they rapidly cool to the floor temperature. (ii) This leaves a large pressure imbalance leading to cloud contraction (first column). Note that the cloud does not shatter during the contraction phase, as one might expect. Instead, strong density perturbations and hot gas penetration arise due to Rayleigh Taylor instabilities similar to those which arise in supernovae, except this is an implosion rather than an explosion. The pressure in the cloud overshoots that of the surroundings, leading to (iii) a rapid expansion phase (second column). As it expands, the cloud (iv) fragments into smaller pieces (‘shatters’; third column). This shattering is almost certainly driven by Richtmyer-Meshkov instabilities as the expansion front sweeps over the strong density inhomogeneities created during the contraction phase, creating strong vorticity and breaking up the cloud. We tested this by allowing a similarly overpressurized but uniform cloud to rapidly expand; in this case shattering does not occur.

Crucially, the cloud evolution now diverges. As seen in the fourth and fifth columns of Fig. 4, the cloudlets can either (v; a) disperse in the surrounding of the original cloud (bottom panels), or (v; b) fall back and coagulate into larger clouds (top panels). The remaining (or re-forming) larger
The evolution of shattering. The upper (lower) row shows snapshots from simulations with \( \chi_f \sim 10 \) and \( T_{cl}/T_{h\text{out}} \sim \{20, 40\} \), and thus \( \chi_f \sim 200 \) (400), respectively. The time \( \Delta t \) is measured relative to the first contraction. Each row shows the process of initial contraction, expansion (with clear fragmentation), shattering (leading to the formation of many “droplets”), and finally coagulation – where the droplets merge back again onto the larger cold gas structures. The simulation with the larger \( \chi_{\text{floor}} \) (shown in the lower row) shows less merging as can also be seen in Fig. 5 (where the line color matches the labels in the first panel of this figure).

![Figure 4](image)

**Figure 4.** The number of clumps (with \( T < 2T_{\text{floor}} \)) as a function of time for simulations with \( \chi_f \sim 10 \) and \( T_{cl}/T_{h\text{out}} \sim \{20, 40\} \). The thicker lines (in red & blue) are the simulations shown in Fig. 4. While all clouds break up into small pieces initially, the efficiency of subsequent coagulation determines the final outcome.

![Figure 5](image)

**Figure 5.** The number of clumps (with \( T < 2T_{\text{floor}} \)) as a function of time for simulations with \( \chi_f \sim 10 \) but different \( \chi_f \) and cloud sizes (denoted by the color and linestyle, respectively). The thicker lines (in red & blue) are the simulations shown in Fig. 4. While all clouds break up into small pieces initially, the efficiency of subsequent coagulation determines the final outcome.

Thus, while `shattering' always begins in a large cloud out of pressure balance, whether it prevails depends on a competition between breakup and coagulation. This can be quantitatively seen in Fig. 5 where we show the number of cloudlets as a function of time. The solid lines depict \( r_{cl}/r_{\text{shatter}} \sim 10^3 \) (for which \( \chi_{\text{crit}} \sim 300 \)), and \( \chi_f = \{1, 2, 3, 4\} \times 100 \). These all show fragmentation into \( \gtrsim 100 \) pieces at \( t \sim 2t_{\text{sc, floor}} \), the point of maximum expansion. However, for \( \chi_f < \chi_{\text{crit}} \), the droplets coagulate, reversing the shattering process, while \( \chi_f \gtrsim \chi_{\text{crit}} \) for the number of droplets remains stable or increases. The dashed line shows that coagulation is more efficient for a larger cloud (i.e. \( \chi_{\text{crit}} \) increases).

### 4 DISCUSSION & CONCLUSIONS

In this work we revisit the `shattering' mechanism first identified by M18 in 2D simulations; we now do so in 3D. Our simulations are governed by 3 dimensionless parameters: the initial cloud overdensity \( \chi_i \), the initial cloud size \( r_{cl}/r_{\text{shatter}} \), and the pressure contrast \( P_{cl}/P_{\text{hot}} \approx T_{\text{floor}}/T_{cl} \). As anticipated, we find that a cloud must be large (\( r_{cl}/r_{\text{shatter}} \gg 1 \)) and out of pressure balance (\( P_{cl}/P_{\text{hot}} \lesssim 0.5 \)) to shatter. However, we also find an unexpected requirement that the final overdensity \( \chi_f \gtrsim \chi_{\text{crit}} \approx 300 \), with a weak scaling on cloud size. Otherwise, the fragments quickly merge. For \( T_{\text{floor}} \sim 10^3 \text{ K} \), this suggests that shattering is inefficient in gas with \( T_{\text{hot}} < 3 \times 10^6 \text{ K} \). We also show that shattering occurs during linear thermal instability \( \delta \rho/\rho \ll 1 \). Hitherto, shattering has only been demonstrated for large, non-linear overdensities.

We find that `shattering' is really a spectrum spanned by the dispersal of cloudlets and their merger. On the ends of this spectrum lie clouds which `explode' when they cool, violently launching the droplets in all directions, and clouds where the restoring coagulation force is so strong that they never break up but instead pulsate. In between, the fate of cold gas depends on the competition between breakup and coagulation, which is governed by the final overdensity \( \chi_f \). Coagulation was already seen in the original 2D simulations of M18 (see their fig. 3, third panel from top, and fig. 6, and associated discussion), but its true importance is only now apparent.

What drives coagulation? There are at least two causes: (i) radiative cooling, which drives pressure gradients in mixed interstitial gas, the source of mass growth discussed...
in Gronke & Oh (2018, 2019). Cooling-induced coalescence has also been highlighted in Elphick et al. (1991); Waters & Proga (2019), though merger velocities seen in those 1D (i.e., no turbulence or mixing), low overdensity ($\chi \sim$ few) calculations are much smaller than seen there, and could not compete with breakup. (ii) Turbulence. It is well known that clumping instabilities driven by particle inertia or wave-particle resonance operate in dust-gas interactions (e.g., Lambrechts et al. 2016; Squire & Hopkins 2018), and may also operate in cloudlet-gas interactions.

Because we do not have a quantitative understanding of the coagulation, we cannot derive a quantitative criterion for shattering. Nonetheless, it seems physically reasonable that the competition between ‘launching’ and ‘drag’ depends on overdensity $\chi$ (which sets the particle stopping length). For coagulation driven by cooling, we can make the following heuristic argument. Suppose that the dispersion of cloudlets is set by the RM instability. The hot gas punches through pressure gradients with a characteristic velocity $c_{\text{hot}}$, and cold clouds disperse with a characteristic velocity $\sim \alpha c_{\text{hot}}$, where $\alpha$ encodes imperfect entrainment. Over a cloud oscillation time, the cloudlets disperse over a volume $V_{\text{launch}} \sim (\alpha c_{\text{hot}}n_{\text{cloud}})/(\rho_{\text{hot}})$. On the other hand, the volume of interstellar hot gas which is consumed by the cloudlets over this time is $V_{\text{hot}} \sim n_{\text{cloud}}V_{\text{hot}} \sim r_{\text{shatter}}^3/(\rho_{\text{shatter}})^1/4$, where we have used the mass entrainment rate $\dot{m} \sim r_{\text{shatter}}^3n_{\text{min}}$ where $n_{\text{min}} \sim \rho_{\text{cloud}}/(\rho_{\text{cloud}}/n_{\text{cloud}})^{1/4}$ (Ji et al. 2019; Gronke & Oh 2019). For the cloudlets to disperse faster than interstellar hot gas can be consumed, we require $V_{\text{launch}} \gtrsim V_{\text{hot}}$. Using $c_{\text{hot}}n_{\text{cloud}} \sim \chi_{\text{init}}^{1/2}$ yields $\chi \gtrsim \alpha^{-2} (r_{\text{shatter}}/c_{\text{hot}})^{1/6}$, which agrees with our findings for $\alpha \sim 0.12$ (cf. dashed line in Fig. 3). This argument illustrates basic considerations; we will study the problem further.

Besides thermal instability, our setup can also mimic cold clouds (with large $\chi \gtrsim 100$) engulfed by a shock, where the background pressure rises rapidly. Using the shock jump conditions, one can relate $\chi_{\text{crit}} \sim \max(300, \chi_{\text{init}})$ to a requirement for the Mach number of the wind to depend on the cloud to shatter: $M^2 \gtrsim (\gamma + 1)/\chi_{\text{crit}} + (\gamma - 1)/\gamma_{\text{crit}}$, which corresponds to $M \sim 1.6$ for $\chi \sim 100$. This is roughly consistent with our wind-tunnel setup in Gronke & Oh (2019) where our fiducial $M = 1.5$ setup was numerically converged, while the higher Mach-number runs (with $M = 3$ and $M = 6$) were not. We attributed this to the larger compression of the cloud, but breakup via shattering also drive resolution requirements. In the $M \sim 1.5$ runs, a solid ‘tail’ behind the cloud forms quickly, while the tail in $M = 6$ simulation is much more diffuse and transient.

Regardless, the competition between breakup and coagulation will differ when there are background gas motions. It is not at all clear that clouds subject to a wind can both shatter and survive; the pieces need to coagulate into larger fragments ($> c_{\text{cold},\text{mix}}$) to survive (e.g., as in fig. 6 of M18). It may well be that while clouds can entrain and grow in transonic winds, they do not survive higher Mach number winds, where shattering into small fragments dominates. The impact of background turbulence is also unclear: it could drive fragmentation, or clumping and coagulation (as for dust). These issues require high resolution simulations with careful attention to convergence. Overall, our physical understanding of the shattering/coagulation mechanisms, and their interaction with extrinsic turbulence, magnetic fields, and cosmic rays, remain tenuous. We will pursue such questions in future work.

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