GMC Collisions as Triggers of Star Formation. V. Observational Signatures

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Abstract

We present calculations of molecular, atomic, and ionic line emission from simulations of giant molecular cloud (GMC) collisions. We post-process snapshots of the magnetohydrodynamical simulations presented in an earlier paper in this series by Wu et al. of colliding and non-colliding GMCs. Using photodissociation region (PDR) chemistry and radiative transfer, we calculate the level populations and emission properties of the transitions of \(^{12}\)CO \(J = 1-0\), \([\text{C} I]\) \(^3\)P\(_0\) \(\rightarrow\) \(^3\)P\(_0\) at 609 \(\mu\)m, \([\text{C} II]\) 158 \(\mu\)m, and \([\text{O} I]\) \(^3\)P\(_1\) \(\rightarrow\) \(^3\)P\(_0\) at 63 \(\mu\)m. From emission maps of integrated intensity and position–velocity diagrams, we find that fine-structure lines, particularly \([\text{C} II]\) 158 \(\mu\)m, can be used as a diagnostic tracer for cloud–cloud collision activity. These results hold even in more evolved systems in which the collision molecular signature in line emission has been diminished.

Key words: ISM: clouds – ISM: kinematics and dynamics – ISM: lines and bands – ISM: magnetic fields – ISM: structure – methods: numerical

1. Introduction

Giant molecular cloud (GMC) collisions are a potential mechanism for triggering star formation activity in such clouds (e.g., Scoville et al. 1986; Tan 2000; Duarte-Cabral et al. 2010; Higuchi et al. 2010; Fukui et al. 2014; Balfour et al. 2015; Torii et al. 2017a). Models of galactic shear-driven collisions (Gammie et al. 1991; Tan 2000; Tasker & Tan 2009; Dobbs et al. 2015) may help explain global galactic star formation relations (Tan 2010; Suwannajak et al. 2014). GMC collisions may also be an important mechanism for driving turbulence within GMCs (Tan et al. 2013; Jin et al. 2017; Li et al. 2017). Thus it is important to develop theoretical and numerical models for such collisions and then use them to calculate the observational signatures of these events (e.g., Duarte-Cabral et al. 2011; Inoue & Fukui 2013; Takahira et al. 2014; Haworth et al. 2015a, 2015b).

With the above goal in mind, this paper continues the works of Wu et al. (2015, 2017b) (Papers I and II) in studying GMC collisions via ideal magnetohydrodynamic (MHD) simulations. In particular, Paper II studied the kinematics and dynamics of collisions of turbulent, magnetized, multiphase (via photo-dissociation region (PDR)-based heating/cooling functions) GMCs using synthetic observations in the optically thin limit. Here, we provide a more realistic treatment of the radiative transfer of line emission from multiple species from these simulations with a tool we develop that accounts for velocity-dependent optical depth along the line of sight. Other papers in this series have added additional physics: Wu et al. (2017a) (Paper III) incorporated star formation via various sub-grid models, including simulations in which star formation depends on the local ratio of mass to magnetic flux; Christie et al. (2017) (Paper IV) studied the effects of ambipolar diffusion, especially its effects on the efficiency of dense core formation. However, here, with our focus on observational signatures, especially on the larger, global scales of the GMCs, we return to the simulation outputs of Paper II for our analysis. We note that these simulations do not include star formation or any localized feedback, so the results we present will isolate the “pure” signature of the GMC–GMC collision process, separate from these complicating factors.

Our paper is organized as follows. In Section 2 we give a brief outline of the snapshots we selected of the MHD simulations performed in Paper II (Section 2.1), of the PDR calculations (Section 2.2), and of the radiative transfer tool we develop (Section 2.3). In Section 3 we discuss the signatures frequently used by the observational community to identify cloud–cloud collision activity. In Section 4 we report our results, which are then further discussed in Section 5. We conclude in Section 6.

2. Numerical Methods

2.1. Magnetohydrodynamical Simulations

For the purposes of this work we use two snapshots from the three-dimensional MHD simulations performed in Paper II. These simulations include self-gravity, supersonic turbulence, and magnetic fields (treated in the limit of ideal MHD). They have been performed with the adaptive-mesh refinement (AMR) code ENZO (Bryan et al. 2014).

The two GMCs considered are initially spherical and uniform with total H-nucleus number density of \(n_{HI} = 100 \text{ cm}^{-3}\), radius of \(R = 20 \text{ pc}\), and thus with mass of \(M = 9.3 \times 10^4 M_{\odot}\). As described in Paper II, for simplicity the mean particle mass was set to a constant value of \(\mu = 2.33 m_{HI}\), where \(m_{HI}\) is the mass of the hydrogen atom. In addition, a constant adiabatic index of \(\gamma = 5/3\) was adopted as the most appropriate single-valued choice for a focus on the dynamics of the molecular clouds. The ambient medium around the GMCs consists of gas with \(n_{HI} = 10 \text{ cm}^{-3}\). The spatial resolution of the AMR grid has a minimum value of 0.125 pc. A magnetic field with strength \(B = 10 \mu G\) has been included, directed at an angle of \(\theta = 60^\circ\) with respect to the \(x\)-direction. The centers of the GMCs have an initial separation of \(2R\) in the \(x\)-direction and 0 in the \(z\)-direction. Along the \(y\)-direction they are offset by an impact parameter \(b = 0.5R\). Both GMCs have a one-dimensional turbulent velocity dispersion of \(\sigma_v = 5.2 \text{ km s}^{-1}\).
As described in Paper I, the simulations include PDR-based heating and cooling processes to determine gas and dust temperature and the emission properties from various species. We note that these heating and cooling functions are applied to both the GMCs and the ambient medium, so that the thermal and chemical evolution of the gas across the atomic to molecular transition is well modeled. An isotropic far-UV (FUV) radiation field with strength $G/G_0 = 4$ (i.e., four times the estimate of the local FUV intensity from Habing 1968) and a cosmic-ray ionization rate of $\zeta_{CR} = 10^{-16} \text{s}^{-1}$ have been adopted. These values represent conditions observed in the inner part of the Galaxy at distances of $\sim 4 \text{kpc}$ from the Galactic Center. Further details are discussed in Papers I and II.

We select two different cases from the above set of simulations: (i) the case where the clouds collide at a relative speed of $v_{rel} = 10 \text{ km s}^{-1}$ (“colliding”) in which they are moving at equal but opposite velocities along the axis of collision (i.e., $v_{rel}/2 = +5 \text{ km s}^{-1}$ and $-v_{rel}/2 = -5 \text{ km s}^{-1}$), and (ii) the case where the clouds do not collide (“non-colliding”) but overlap each other along the line of sight, and therefore the relative speed is $v_{rel} = 0 \text{ km s}^{-1}$. The selected snapshots for the colliding case are at times of $t = 2$ and 4 Myr and are shown in the top and middle rows of Figure 1. The collision occurs along the $x$-direction. For the non-colliding case, we consider only the snapshot at $t = 4$ Myr, which is shown in the bottom row of Figure 1.

### 2.2. 3D-PDR Calculations

To perform realistic radiative transfer calculations (see Section 2.3) and obtain the emission map of a particular line, we need knowledge of the corresponding level populations, abundances of species, as well as temperature profiles of the gas and dust. To do this, we use the 3D-PDR code5 (Bisbas et al. 2012), which treats the chemistry of PDRs using various cooling and heating processes. Although the code is able to calculate three-dimensional PDRs of arbitrary density distributions, the computational cost for post-processing the above hydrodynamical snapshots at the given resolution is prohibitively high. Instead, we adopt an extended one-dimensional grid of slabs of uniform density irradiated by a plane-parallel radiation field and we adopt the methodology described in Paper I, which connects the H-nucleus number density $n_H$ of a cell with a most probable visual extinction value, $A_V$.

The density range spanning the grid of one-dimensional simulations is $1 \text{ cm}^{-3} < n_H < 10^7 \text{ cm}^{-3}$, with a sampling every 0.1 dex. This resolution gives a total set of 70 simulations. In all these calculations we considered a plane-parallel radiation field with strength $\chi/\chi_0 = 4$ and a cosmic-ray ionization rate of $\zeta_{CR} = 10^{-16} \text{s}^{-1}$, thus mimicking the conditions adopted in Papers I and II. We utilized a reduced UMIST 2012 chemical network (McElroy et al. 2013) of 33 species and 330 reactions and we adopted the “standard” abundances of elements in the interstellar medium (ISM), i.e., $[\text{He}] / [\text{H}] = 0.1$, $[\text{C}] / [\text{H}] = 10^{-4}$, and $[\text{O}] / [\text{H}] = 3 \times 10^{-4}$ (Cardelli et al. 1996; Cartledge et al. 2004; Röllig et al. 2007).

There is generally good agreement between the grids of 1D simulations of Wu et al. (2015), which used the simpler Py-PDR code, and this work. However, in the low-density medium that corresponds to low values of $A_V$ we do find some differences in abundances and other properties, which is not

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5 http://ucolchem.github.io/3dpdr.html
unexpected since PDR codes often deviate in this regime (Röllig et al. 2007). This leads to moderate differences in the calculated mass-weighted gas temperature of Figure 1 in comparison with Wu et al. (2017b).

2.3. Radiative Transfer Calculations

We construct a radiative transfer tool described in the Appendix, which we use for our synthetic observations. As mentioned in Section 2.1, the MHD simulations use an AMR grid, effectively meaning that the spatial resolution is higher in places of higher density. For the radiative transfer calculations, however, we convert the selected snapshots to a uniform grid of 0.125 pc resolution. This in turn gives a grid consisting of $512^3$ cells, which we use to solve for the radiative transfer along each line of sight.

Once the radiative transfer equation is solved (see the Appendix), we calculate the antenna temperature, $T_A$, using the following relation:

$$ T_A = \frac{c^2 I_v}{2 k_B \nu^2}. $$

(1)

Here, $c$ is the speed of light, $k_B$ is the Boltzmann constant, and $I_v$ is the intensity over frequency $\nu$, defined as

$$ \nu = \nu_0 \left(1 - \frac{v_{\text{los}}}{c}\right), $$

(2)

where $\nu_0$ denotes the frequency in the observer’s reference frame and $v_{\text{los}}$ is the velocity along the line of sight. The integrated antenna temperature over velocity, $W$, is evaluated as

$$ W = \int T_A dv_{\text{los}}, $$

(3)

where the velocity width adopted to construct the emission maps is $-15 \text{ km s}^{-1} < v_{\text{los}} < +15 \text{ km s}^{-1}$.

Unless otherwise stated, the radiative transfer algorithm has been applied along the $x$-direction, which is the axis of collision. The chosen direction of integration is from $+x$ to $-x$, i.e., the observer is located in the $-x$ direction. With the collision occurring along the line of sight, we expect to see the clearest signature of its effects in velocity space in this limiting case. However, we will also examine how the GMCs appear when viewed from a direction perpendicular to the collision axis, which is the other extreme, i.e., for which the signatures of the collision would be minimized.

3. The “Bridge-effect” Signature

An observational technique to identify a collision event between two clouds is to construct their position–velocity ($p$–$v$) diagram and look for two velocity peaks along the line of sight. Each velocity peak corresponds to one individual cloud. In the $p$–$v$ diagram, the peaks in $T_A$ along the velocity axis at a particular position should be connected via a “bridge” of lower $T_A$. This “bridge effect” indicates the presence of a pair of clouds along the line of sight that are connected by gas at intermediate velocities between the two main values of each cloud, implying a mutual interaction. Otherwise (i.e., when the velocity peaks are not connected but remain isolated), one may simply see two different clouds along the line of sight that are not interacting with one another.

Bridged velocity peaks have been observed in various cases. For example, C$^{18}$O $J = 1$–0 observations in the Serpens star-forming region by Duarte-Cabral et al. (2010) confirm the existence of a double peak in the $p$–$v$ diagram. The corresponding velocity width has been estimated as $\sim 2 \text{ km s}^{-1}$. They explain this feature using smoothed particle hydrodynamics (SPH) simulations of two colliding cylinders (Duarte-Cabral et al. 2011) in which the resulting $p$–$v$ diagram is reminiscent of the one observed in the Serpens region. Torii et al. (2011) provide $p$–$v$ diagrams of the Trifid Nebula (M20) in which a broad bridge effect connecting multiple velocity peaks along the line of sight is observed. Similarly, Nakamura et al. (2012) presented images at high spatial resolution of the $^{12}$CO $J = 1$–0 line for a wide region including the L1641-N cluster. They find gas with two velocity components along the line of sight, suggesting a cloud–cloud collision event. The velocity width is $\sim 3 \text{ km s}^{-1}$, which is about three times higher than the local turbulent velocity ($v_{\text{turb}} \sim 1 \text{ km s}^{-1}$). Recently, Fukui et al. (2017a) identified double velocity peaks in the $^{12}$CO $J = 1$–0 line of the molecular gas toward M42 and M43, which potentially implies that the northern part of the Orion A cloud may have been formed by two colliding clouds.

Using hydrodynamical simulations, Haworth et al. (2015a, 2015b) discuss extensively how the bridge effect occurs and develops in $p$–$v$ diagrams of the $^{12}$CO $J = 1$–0 line. They examine various cases and at different viewing angles of colliding and non-colliding cases, and they additionally examine $p$–$v$ diagrams of isolated clouds. They also include modeling of radiative feedback (i.e., H II regions) generated by stars forming in their simulations. They find that the bridge feature holds for a small fraction of all possible viewing angles (e.g., about 20%–30% for a head-on collision at $v_{\text{rel}} = 10 \text{ km s}^{-1}$, which is the collision velocity considered here) and is thus sensitive to the point of view of the observer. Furthermore, they find that this signature, when the geometry is favorable for its detection, is resilient to radiative feedback from stars formed in the simulations and cannot be easily reproduced by kinematic behavior other than a cloud–cloud collision. A bridged double velocity peak can therefore act as a signature of an undergoing collision event.

Lines other than low-$J$ CO (including isotopologues) have not been widely considered as diagnostic tracers for GMC–GMC collisions. However, Gerin et al. (2015) presented a detection of [C II] 158$\mu$m at position G49.5-0.4 in W51A, in which strong emission from two velocity components is reported, i.e., $T_A \sim 30 \text{ K}$ and $\sim 25 \text{ K}$ for velocities of $\sim 55$ and $\sim 70 \text{ km s}^{-1}$, respectively. This implies a relative velocity of $v_{\text{rel}} \sim 15 \text{ km s}^{-1}$. W51A is considered to be a strong candidate for GMC–GMC collision activity (Ginsburg et al. 2015), and these observations therefore suggest that fine-structure lines may be possible diagnostic indicators for cloud collision events.

4. Results

We construct emission maps of integrated intensity and $p$–$v$ diagrams for all three simulation snapshots considered (two for the colliding case at $t = 2$ and 4 Myr and one for the non-colliding case at $t = 4$ Myr). Our standard $p$–$v$ diagrams are calculated by averaging over the entire $y$-direction at each different velocity, $v$, as a function of the $z$-direction. To highlight the bulk motions that are a signature of a cloud collision, we also show maps of integrated intensity of only

\footnotetext[5]{Following the notation of Draine (2011).}
higher velocities, i.e., $>+5 \text{ km s}^{-1}$ (redshifted) and $<-5 \text{ km s}^{-1}$ (blueshifted). This emission will mostly correspond to gas that moves at velocities greater than those reached due to internal turbulence. We focus our consideration on four different lines: $^{12}\text{CO } J = 1-0$ (hereafter $\text{CO } J = 1-0$), $[\text{C}\ I] (609 \mu\text{m})$, $[\text{C}\ II] 158 \mu\text{m}$, and $[\text{O}\ I] 63 \mu\text{m}$.

4.1. Colliding Case

4.1.1. Fiducial Results: Comparison of CO and Atomic Fine-structure Lines

Figure 2 shows the emission maps (integrated intensity, $W$) and the corresponding $p-v$ diagrams for the colliding case at $t = 2$ Myr and 4 Myr for all different lines considered. The bottom row shows the high-velocity gas emission for each case, which we discuss further below. These figures illustrate how each different species reveals different parts of the clouds and their surroundings.

The collision occurs along the line of sight. Columns from left to right: $\text{CO } J = 1-0$, $[\text{C}\ I] 609 \mu\text{m}$, $[\text{C}\ II] 158 \mu\text{m}$, $[\text{O}\ I] 63 \mu\text{m}$. The bottom row shows the integrated intensity of high-velocity gas traced by each line at $t = 4$ Myr, i.e., it maps the gas that has velocities $>+5 \text{ km s}^{-1}$ (red contours) and $<-5 \text{ km s}^{-1}$ (blue contours). The contours correspond to the intensity of the line. The grayscale shows the total intensity, $W$, of each line. In the $p-v$ diagrams and at $t = 2$ Myr, the “bridge effect” is better seen in the fine-structure lines of $[\text{C}\ II]$, $[\text{O}\ I]$, and partially in the $[\text{C}\ I]$ line, as all these are primarily emitted from the lower-density gas, including from the ambient atomic medium, that has not yet undergone collision. Since $\text{CO } J = 1-0$ is emitted from the innermost part of both clouds where FUV radiation has been severely extinguished, identifying the collision signature in this line once the clouds start to merge is more difficult. Once the collision further evolves ($t = 4$ Myr), the bridge effect is also diminished for the $[\text{C}\ I] 609 \mu\text{m}$, although it still holds in $[\text{C}\ II] 158 \mu\text{m}$ and $[\text{O}\ I] 63 \mu\text{m}$ lines. The maps of high-velocity gas, on the other hand, show a collision event at $z \sim -10 \text{ pc}$ and $y \sim +10 \text{ pc}$ in $\text{CO } J = 1-0$ and $[\text{C}\ I] 609 \mu\text{m}$, with the rest of the fine-structure lines indicating the bulk movement of GMCs and ambient medium on larger scales.
extinguishes the ambient FUV radiation field. In the \( p-v \) diagrams, while the two velocity components of the original GMCs are just about discernible at 2 Myr, overall, and especially by 4 Myr, the emission becomes dominated by gas that has been compressed in the collision, i.e., near zero velocity in the simulation frame. Thus a bridge-effect signature linking two distinct peaks is not a characteristic feature of the CO \( J = 1-0 \) emission at these times.

We performed two additional investigations related to the molecular gas emission. First, we examined the equivalent \( p-v \) diagrams of CO \( J = 3-2 \), which originates from relatively dense molecular gas. We found that these \( p-v \) diagrams exhibit very similar morphologies to those of CO \( J = 1-0 \). Second, we constructed the \( p-v \) diagram of the CO \( J = 1-0 \) at \( t = 1 \) Myr, i.e., at an earlier stage of the evolution. We found that at this stage, the bridge-effect signature linking two distinct peaks was clearly visible, although its brightness temperature was much lower than that shown in Figure 2, since relatively fewer higher-density clumps were present at these earlier times.

The \([\text{C} \text{I}]\) 609 \( \mu \)m line is primarily emitted from the more diffuse gas of both GMCs and hence it reveals the majority of the molecular gas of the clouds (see also Papadopoulos et al. 2004; Offner et al. 2014; Bisbas et al. 2015, 2017; Glover & Clark 2016). Note that its intensity remains approximately constant as time increases from \( t = 2 \) to \( t = 4 \) Myr.

The fine-structure line of \([\text{C} \text{II}]\) 158 \( \mu \)m is emitted from the outer parts of both GMCs, since it is produced by the interaction with the isotropic FUV radiation field. This line is also emitted from the surrounding ambient medium, i.e., the ISM gas that is here set up as an idealized representation of atomic cold neutral medium with initial \( n_{i} = 10 \) cm\(^{-3}\) but is also moving alongside each GMC and so forming a shock-compressed layer near zero velocity (see Paper II). The relative importance of the emission from the ambient medium compared to that from the GMCs is discussed below. In Figure 2 we notice that the \([\text{C} \text{II}]\) emission decreases in intensity from 2 to 4 Myr, which reflects the conversion of more material from the clouds in CO-emitting structures.

Similarly to \([\text{C} \text{II}]\) 158 \( \mu \)m, the \([\text{O} \text{I}]\) 63 \( \mu \)m line, although much weaker than all the above lines, originates from the outermost parts of both clouds and with significant contributions from the ambient medium. The 63 \( \mu \)m line is optically thick, and due to this, its intensity is noticeably reduced at the parts of the map that correspond to high column densities (see Figure 1). The blueshifted component in the \( p-v \) diagrams (i.e., for \( v_{\text{los}} \approx -5 \) km s\(^{-1}\)) has a reduced antenna temperature compared to the redshifted component. The three well-defined stripes of antenna temperature correspond to the contribution of the ambient medium. The upper and lower stripes are due to the redshifted and blueshifted components respectively (moving away from and toward the observer at a constant speed of \( v_{\text{rad}} \approx 5 \) km s\(^{-1}\)). The central stripe is mostly due to the shock-compressed ambient medium (see Section 4.1.2). We further note that the \([\text{O} \text{I}]\) line, and in particular its ratio with \([\text{C} \text{I}]\) 609 \( \mu \)m, can be used as a diagnostic of the intensity of the FUV radiation in PDRs (see Bisbas et al. 2014).

Summarizing the above results, the \( p-v \) diagrams in all cases span a width in velocity space \( \approx 10 \) km s\(^{-1}\), i.e., resulting from the relative motion of the two clouds, that is larger than that due to internal turbulence within the initial GMCs, i.e., \( \approx 5 \) km s\(^{-1}\). Once the collision process begins, \( W_{\text{CO}(1-0)} \) becomes enhanced. The motion of the gas then becomes more turbulent due to the collision as the two GMCs merge. This is reflected in the \( p-v \) diagram at \( t = 4 \) Myr in which the overall width in velocity space has increased. As a result, the feature of double velocity peaks that could indicate collision is diminished (see also Haworth et al. 2015a), although at the position \( \approx -10 \) pc (where the collision occurs) the intensity is quite strong over most of the velocity width of \( \approx 20 \) km s\(^{-1}\). The \( p-v \) diagram of the \([\text{C} \text{I}]\) 609 \( \mu \)m line at \( t = 2 \) Myr indicates, however, that such a feature is reminiscent of the bridge effect discussed in Section 3 and in particular at position \( \approx 0 \) pc. As time progresses and the clouds merge (\( t = 4 \) Myr), this signature disappears.

For systems whose collision is evolved to the point of erasing or diminishing any potential bridge-effect feature in the low-J CO \( p-v \) diagram, fine-structure lines may be promising alternatives to be diagnostics for such activity. This can be seen in the \( p-v \) diagrams of \([\text{C} \text{II}]\) 158 \( \mu \)m and \([\text{O} \text{I}]\) 63 \( \mu \)m; these two lines give the most prominent signature of cloud–cloud collision, as the bridge effect linking two distinct peaks can now be clearly seen. However, as discussed above, the emission of both \([\text{C} \text{II}]\) 158 \( \mu \)m and \([\text{O} \text{I}]\) 63 \( \mu \)m lines originate mostly from the outer envelope of both GMCs and the surrounding ambient ISM gas, some of which corresponds to gas that has not yet suffered any collision and still carries information on the relative velocity of the GMCs prior to collision. These lines can thus be used in order to identify and/or clarify the collision process in systems whose low-J CO lines may provide limited information.

The bottom row of Figure 2 shows the high-velocity gas traced by each line. These maps correspond to the \( t = 4 \) Myr snapshots. The grayscale shows the total intensity, \( W_{\text{C}} \), of each line. Red contours correspond to redshifted gas with velocities \( v > +5 \) km s\(^{-1}\) and blue contours to blueshifted gas with velocities \( v < -5 \) km s\(^{-1}\). In both cases, the contours correspond to the intensity of the line. We do not include velocities in the range \( -5 < v < +5 \) km s\(^{-1}\) because we want to isolate the bulk motion of the gas due to collision and the mutual interaction of the GMCs rather than additionally mapping the width reached due to turbulence. The Doppler shifts of both the CO \( J = 1-0 \) transition and the \([\text{C} \text{I}]\) 609 \( \mu \)m line reveal the collision at \( z \approx -10 \) pc and \( y \approx +10 \) pc corresponding to the region with the highest density. However, the fine-structure line of \([\text{C} \text{II}]\) 158 \( \mu \)m reveals the bulk movement of the GMCs and is thus a good indicator of the cloud–cloud collision.

4.1.2. Contribution of the Ambient Medium and the Utility of the 158 \( \mu \)m Line as a Diagnostic of Cloud–Cloud Collisions

Emission from the ambient, lower-density medium can become important when studying the above fine-structure lines in these simulations. To clarify the contribution of this gas in our results, we calculate the \( p-v \) diagrams of \([\text{C} \text{II}]\) 158 \( \mu \)m and \([\text{O} \text{I}]\) 63 \( \mu \)m lines emitted by densities \( n_{H} > 20 \) cm\(^{-3}\) for the case at \( t = 2 \) Myr. For densities below 20 cm\(^{-3}\); we consider a negligible contribution in optical depth. This ensures that the \( p-v \) diagram will contain information that is essentially only from the GMCs. These results are shown in Figure 3: the upper row shows the total emission and the bottom row shows the “GMC-only” emission. The bridge effect is seen in the \( p-v \) diagram of \([\text{C} \text{II}]\) 158 \( \mu \)m, because it is primarily emitted from the outer envelopes of the GMCs. Indeed, for our particular setup the GMC-only emission appears stronger since in the
total case absorption from the ambient medium acts to diminish the signature of the collision. This may indicate an important role for $[13\text{C}\ II]$ observations to complement $[\text{C}\ II]$ studies (e.g., Goicoechea et al. 2015).

On the other hand, $[\text{O}\ I] 63\mu m$ is mainly emitted from the ambient medium, and removing the contribution of the latter from our calculations results in a very low brightness temperature (note that $T_A$ in the bottom right panel of Figure 3 is enhanced by a factor of 10). We thus find that the fine-structure line of $[\text{O}\ I] 63\mu m$, being dominated by the ambient medium, is not, on its own, a good tracer of GMC–GMC collisions, but rather can give information on colliding atomic flows. However, since molecular clouds are known to have significant atomic halos (e.g., Andersson et al. 1992; Wannier et al. 1999) $[\text{O}\ I]$ observations may still provide important complementary information for understanding particular collision candidates.

By design, the treatment of the ambient atomic medium in the simulations of Wu et al. (2017b) is highly idealized. In particular, no internal turbulence is included in this component. Thus to explore potential effects of such turbulence, for the case of the $[\text{C}\ II] 158\mu m$ line emission, we perform an additional radiative transfer calculation in which we assume an enhanced turbulent velocity (in post-processing) of $v_{\text{turb}} = 10\text{ km s}^{-1}$ (see Equation (8)) for densities below $20\text{ cm}^{-3}$. Figure 4 shows the $p$–$v$ diagram of this test. Comparing this with the corresponding diagram in Figure 2 (top left panel), we see that the velocity width is now increased and that the brightness temperature is moderately decreased. This is due to increased optical depth from the ambient medium over the range of velocities of $[\text{C}\ II]$ emission from the GMCs. Still, we find that the bridge effect is resilient to the uncertainties introduced from the emission of the ambient medium and that the $[\text{C}\ II] 158\mu m$ line is thus an important and useful diagnostic for GMC–GMC collisions.

The utility of $[\text{C}\ II] 158\mu m$ as a diagnostic of cloud–cloud collisions is further demonstrated in Figure 5, in which the upper panel shows a map of the high-velocity gas at $t = 4\text{ Myr}$ and where we exclude the contribution of the ambient medium. Extended parts of the high-velocity gas overlap, particularly in the region corresponding to the densest part of the colliding GMCs and where star formation is likely to be triggered (Paper III). We then isolate this part of the emission map to construct a $p$–$v$ diagram corresponding to a cut of only $2\text{ pc}$ width. This $p$–$v$ diagram, also shown in Figure 5, reveals that the emission peaks at distinct velocities are bridged in $p$–$v$ space.

4.1.3. Effect of Viewing Angle—Limiting Case of a Side-on View

In Figure 6 we show the emission map and $p$–$v$ diagram of the $[\text{C}\ II]$ line at $t = 4\text{ Myr}$ when the observation is made perpendicular to the direction of the collision. In this case, any signature of the cloud–cloud collision is minimized, and the
velocity width now is in principle connected with the internal turbulence of the gas. However, the emission map shows a characteristic feature of a rectangular shape spanning ~40 pc (from ~20 to +20 pc) with a bright stripe at \( x \sim 0 \) pc across the \( y \)-axis. This originates from the ambient ISM gas in which both GMCs are embedded. The \( p-v \) diagram shows a single, main component in velocity space. Still, in the typical case one expects some part of the collision axis to be along the line of sight, and the purely perpendicular case will be a relatively unlikely occurrence.

4.2. Non-colliding Case

Figure 7 shows the emission maps, \( p-v \) diagrams, and maps of high-velocity gas for the non-colliding case at \( t = 4 \) Myr. The emission maps in all four different lines are qualitatively similar to the colliding case at this dynamical time (see Figure 2 for comparison). However, the intensities of \( \text{CO} \) \( J = 1-0 \) and \( \text{C I} \) 609 \( \mu \)m are now lower since the system does not reach the necessary high densities, and therefore high column densities, as in the colliding case. On the other hand, the emission maps of [C II] and [O I] lines do not significantly differ from the colliding case. The lower column densities reached in this simulation do not shield the 158 \( \mu \)m line and it thus remains brighter than the corresponding one of Figure 2.

The velocity widths of the \( p-v \) diagrams in Figure 7 are all within the range \(-5 \lesssim \nu_{\text{los}} \lesssim +5\ \text{km \ s}^{-1}\), which results from the turbulent internal motion of the gas in both GMCs. An interesting feature, however, is that the intensity-weighted velocity gradients for the \( \text{CO} \) \( J = 1-0 \) and [C II] 158 \( \mu \)m lines are decreasing along the position axis in the \( p-v \) diagrams. This is due to the mutual gravitational forces attracting the GMCs toward each other in the simulation domain. These gradients are most clearly seen in the maps of high-velocity gas in the bottom row of the figure. Here it can be seen that the redshifted (\( \nu_{\text{los}} > +5\ \text{km \ s}^{-1} \)) and blueshifted (\( \nu_{\text{los}} < -5\ \text{km \ s}^{-1} \)) components do not overlap, as shown in the bottom row of Figure 6, different from the case of cloud–cloud collision. For example, for the particular geometries considered we find a \( \lesssim 17\% \) overlap in the [C II] 158 \( \mu \)m line as opposed to \( \gtrsim 42\% \) in the colliding case (when compared to the upper panel of Figure 5).

5. Discussion

Being able to identify collisions between GMCs is potentially important for our understanding of the global star formation process in galaxies. As discussed in Section 3, observational surveys have revealed several cases of ongoing cloud–cloud collisions using low-\( J \) CO lines as diagnostics. Our work complements these findings by first analyzing the results of realistic MHD simulations of colliding, turbulent, multiphase GMCs, and then exploring how fine-structure lines compare with \( \text{CO} \) \( J = 1-0 \). This work differs from the studies of Haworth et al. (2015a, 2015b) by considering a more...
realistic physical model that includes magnetic fields and PDR-based heating/cooling, a concomitant improved treatment for the abundance and level populations of CO (whereas they assumed a constant abundance of \([CO]/[H] = 8 \times 10^{-5}\) throughout their clouds), and a calculation of the radiative transfer of the fine-structure lines.

Our main finding is that the lines of \([\text{C} \, \text{I}] 609 \mu m\) and \([\text{C} \, \text{II}] 158 \mu m\) are promising alternative ways for identifying cloud-cloud collisions via the bridge effect, linking distinct velocity peaks in \(p-v\) space. The \([\text{O} \, \text{I}] 63 \mu m\) line is highly affected by the contribution of the ambient ISM, so its emission will depend sensitively on the nature of the atomic gas around the GMCs. Such gas has only been treated in a very idealized way in our current simulations, so we are not able to draw strong conclusions about the utility of \([\text{O} \, \text{I}]\) as a diagnostic of GMC–GMC collisions; however, we expect that it may be potentially useful if GMCs have significant co-moving atomic halos. As the collision progresses and the denser parts of the clouds merge, the bridge effect diminishes and low-\(J \, 12\text{CO}\) lines then hardly show any signature of the collision. On the other hand, the lifetime of the broad bridge in fine-structure lines is predicted to be longer since these lines are emitted from the more rarefied parts of GMCs, which are primarily located at their outer envelopes that have not yet undergone collision.

The models considered here are based on an idealized situation in which there is no local stellar feedback. However, cloud–cloud collisions are potential sites for triggered star formation (Fukui et al. 2015, 2017a, 2017b; Torii et al. 2015, 2017a), including leading to the birth of massive, \( \gtrsim 10 \, M_\odot \) stars (Takahira et al. 2014; Balfour et al. 2015). Thus the signatures of the PDRs from such localized stellar feedback (for examples of models of H\(\text{II}\) region feedback see, e.g., Dale et al. 2012; Haworth et al. 2015b; Walch et al. 2015) may confuse those from the bulk original GMC material, externally irradiated. Such contributions also need to be accounted for when interpreting observational data that include localized PDRs, although recent simulations by Torii et al. (2017b) indicate that feedback of such massive stars does not alter the bridge effect in \(p-v\) diagrams of molecular lines, such as low-\(J \, 12\text{CO}\). Thus the models presented here are most useful for isolating the “pure” signature of the GMC–GMC collision, which may be most easily compared to observations of GMCs in relatively early stages of collision and star formation.

Another simplification of our treatment is that in the postprocessing of the MHD simulations, the gas is assumed to be in local thermodynamic equilibrium and additional transient heating effects from shocks are ignored. A future paper in this series will explore the importance of such effects.

As discussed in Section 4, most of our presented results are for the case of the collision occurring along the line of sight of the observer, which is the most idealized situation. In general, the detectability of the bridge-effect signature will diminish as the fraction of the collision axis that is projected along the line of sight decreases. To overcome such effects, statistically significant samples of candidate GMC–GMC collisions need to be considered.

6. Conclusions

In this paper we performed synthetic observations of \(12\text{CO} \ J = 1-0, \ [\text{C} \, \text{I}] 609 \mu m, \ [\text{C} \, \text{II}] 158 \mu m, \) and \([\text{O} \, \text{I}] 63 \mu m\) based on snapshots of MHD simulations of GMC collisions carried out in Paper II of this series. The selected snapshots examine the colliding case of two GMCs, and the non-colliding case of two GMCs that overlap each other along the line of sight of the

Figure 7. As in Figure 2, but now for the non-colliding case. Here we plot the emission maps, \(p-v\) diagrams, and the high-velocity gas for \(t = 4 \, \text{Myr}\) only. From the \(p-v\) diagrams it can be seen that in all cases we find a width of \(<8 \, \text{km} \, \text{s}^{-1}\) corresponding to the turbulent velocity dispersion due to the internal gas motions in each GMC. However, the gravitational forces acting on both clouds result in their mutual attraction. This can be observed in the maps of high-velocity gas in which the upper left part is redshifted and the bottom right is blueshifted. Still, in none of the cases do we observe an interaction pointing to a collision, such as seen in Figure 2.
observer. With a simple radiative transfer tool, we calculated emission maps of integrated intensity (including of high-

velocity components) and position–velocity diagrams for the above lines. We demonstrated that fine-structure lines, and in particular [C II] 158 μm, may be a promising alternative diagnostic of cloud–cloud collisions, separate from the more commonly discussed CO lines. This finding holds even when the collision has been evolved so that the denser regions have merged and low-J CO lines are no longer good tracers of the collision. Our results are summarized as follows:

1. The overall CO $J=1-0$ emission is stronger in the colliding case than in the non-colliding case, and in particular in the region where the collision occurs (peak of the total H-nucleus column density). The $p-v$ diagram in the colliding case does not show a clear signature of the bridge effect, mainly because the collision has been evolved to such an extent that the CO-rich gas has been mixed up and such a signature is diminished. On the other hand, the maps of integrated intensity of blue- and redshifted high-velocity gas do show in a clear way whether or not the two GMCs along the line of sight are colliding.

2. The [C II] $^3P_1 \rightarrow ^3P_0$ transition corresponding to a wavelength of 609 μm is found to be emitted from the more diffuse gas of both GMCs. Although it peaks at the position where the two GMCs collide, it does not fluctuate as much as the CO $J=1-0$ line and its intensity does not significantly differ in the non-colliding case. The bridge effect is observable in the $p-v$ diagram at $t=2$ Myr in the colliding case, but at $t=4$ Myr it has disappeared. As with the CO $J=1-0$ line, the high-

velocity maps are able to indicate the collision event at all times.

3. The fine-structure [C II] 158 μm shows the clearest signature of the bridge effect in the $p-v$ diagrams of the colliding case. This line is emitted from the outermost parts of both GMCs, with modest further contributions from the ambient ISM gas. We find that the contribution of the ambient ISM does not significantly impact the ability of [C II] 158 μm to be a tracer of GMC–GMC collisions. The overall [C II] emission does decrease in time as the collision progresses, since the increase in density shields the FUV radiation. The blue- and redshifted high-velocity gas overlaps almost everywhere in the colliding case.

4. The emission of the [O I] $^3P_1 \rightarrow ^3P_0$ transition at 63 μm is much weaker than that of [C II] at 158 μm, with significant contributions from the ambient atomic ISM gas. It is thus a better tracer of surrounding atomic halos of GMCs, which, depending on their properties, may provide important, complementary information to diagnose GMC–GMC collisions.

All $p-v$ diagrams in the non-colliding case show a velocity width corresponding to internal turbulent gas motions, i.e., at approximately virialized velocities. Furthermore, in all the above cases, we have assumed that the collision occurs along the line of sight of the observer. If the collision is viewed at an angle, then any potential signatures will be diminished, and completely eliminated in cases where the collision occurs mostly perpendicular to the observer. Statistical samples of candidate GMC–GMC collision events are needed to average over such geometric effects.

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**Appendix**

**Radiative Transfer Algorithm**

We describe here the algorithm of radiative transfer calculations we develop, which was used in all synthetic maps in this work (see also Section 2.3). We begin by solving the radiative transfer equation along the line-of-sight element $dz$:

$$
\frac{dl}{dc} = -\alpha_v I_v + \alpha_s S_v, \tag{4}
$$

where $I_v$ is the intensity of the line, $\alpha_v$ the absorption coefficient, and $S_v$ is the source function at frequency $\nu$. The source function and the absorption coefficient for a transition of $i \rightarrow j$ are

$$
S_v = \frac{2\hbar c^3}{c^2} \frac{n_i g_j}{n_j g_i}, \tag{5}
$$

$$
\alpha_v = \frac{c^2 n_i A_{ij}}{8\pi v_0^3} \left( \frac{n_i g_j}{n_j g_i} - 1 \right) \phi_v, \tag{6}
$$

where $v_0$ is the frequency of the line center, $A_{ij}$ is the Einstein $A$ coefficient, $n_i, n_j$ are the level populations, and $g_i, g_j$ are the statistical weights of levels $i, j$, and $\phi_v$ is the line profile. The level populations are obtained from our PDR calculations using 3D-PDR (see Section 2.2 of Bisbas et al. 2012). We assumed a Maxwellian distribution of velocities due to the thermal and turbulent gas motion. The line profile therefore takes the form

$$
\phi_v = \frac{1}{\sqrt{2\pi \sigma_v^2}} \exp \left\{ -\frac{[(1 + v_{los}/c)\nu - v_0]^2}{2\sigma_v^2} \right\}, \tag{7}
$$

where $v_{los}$ is the gas velocity along the line of sight (positive for redshift and negative for blueshift) and $\sigma_v$ is the dispersion defined as

$$
\sigma_v = \frac{v_{los}}{c} \sqrt{\frac{k_B T_{gas}}{m_{mol}}} + \frac{v_{turb}^2}{2}, \tag{8}
$$

where $T_{gas}$ is the gas temperature, $m_{mol}$ is the mass of the molecule/ion emitting the line, and $v_{turb}$ is a root-mean-square measure of turbulent velocities (set to be $v_{turb} = 1.5$ km s$^{-1}$ throughout the radiative transfer calculations presented here).

The formal solution of the radiative transfer equation (Equation (4)) is given by

$$
I_v(z) = I_v(0) e^{-\tau_v} + \int_0^{\tau_v} S_v(z) e^{-\tau_v} d\tau_v', \tag{9}
$$

where $\tau_v = \int z \alpha_v(z') dz'$ is the optical depth. To solve the radiative transfer numerically, the absorption coefficient is assumed to be a linear function of $z$ and the source function is assumed to be a linear function of $\tau$ between adjacent grid points $[z_p, z_{p+1}]$ (see also Andree-Labsch et al. 2017, for alternative ways of solving the radiative transfer equation in...
this limit). Then, the differential solution can be obtained as

\[
I_{\nu, p+1} = I_{\nu, p} e^{-\Delta \tau_\nu} + S_{\nu, p} \left( \frac{1 - e^{-\Delta \tau_\nu}}{\Delta \tau_\nu} - e^{\Delta \tau_\nu} \right)
+ S_{\nu, p} \left( 1 - \frac{1 - e^{-\Delta \tau_\nu}}{\Delta \tau_\nu} \right),
\]

where the subscripts \( p \) and \( p + 1 \) denote the position of variables. This form of the solution can reproduce the physical consequences at both optically thin and thick limits:

\[
I_{\nu, p+1} = \begin{cases} 
I_{\nu, p} (1 - \Delta \tau_\nu) + \frac{\Delta \tau_\nu}{2} B_\nu, & \text{if } \Delta \tau_\nu \to 0, \\
B_{\nu, p+1}, & \text{if } \Delta \tau_\nu \to \infty.
\end{cases}
\]

For boundary conditions, we adopt the intensity of the cosmic microwave background radiation of 2.7 K, i.e., \( I(z) = 0 = B_\nu(2.7 \text{ K}) \) where \( B_\nu \) is the Planck function. The line profile is obtained by solving Equation (9) for the frequency range \([\nu_0 - \Delta \nu/2, \nu_0 + \Delta \nu/2]\), where \(\Delta \nu \ll \nu_0\) is the bandwidth.

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