Cloud-cloud collisions and dense core formation

Asao HABE (Hokkaido Univ.)

collaborators

Elizabeth J. Tasker (ISAS),
K. Shima (Kyoto Univ.), K. Takahira,
N. Sakre (Hokkaido Univ.)
Y. Fujimoto (Australia National Univ.)
introduction

- cloud cloud collision (CCC) is a strong candidate of trigger of high mass star formation
- many papers recently report observational evidence
- recent galaxy simulations show that cloud cloud collisions are frequent
- dense gas clump formation by CCC simulation
Cloud Collision Observations

- Vallee & Avery 1990, Lepine & Duvert 1994
- Hasegawa + 1994, Sato + 2000
- Furukawa + 2009
- Ohama + 2010
- Kang + 2010
- Higuchi + 2011, 2014
- Torii + 2011
- Nakamura + 2012, 2014
- compact star clusters and Spitzer bubbles observations by Nagoya group (Fukui + 2014, Torii + 2015)

many Fukui san’s group papers (PASJ special issue, 2018)
Recent Cloud Collision Observation Papers

CO(J=2-1) and infrared images of NGC3603

- Furukawa+ 2009
- Kang + 2010
- Ohama+ 2010
- Torii + 2011
- Nakamura + 2012, 2014
- Fukui + 2014,
- Higuchi +2014
- Dobashi +2015
- Torii + 2015,
- Tsuboi+2015

$\Delta v \sim 15\text{km/s}$

Fukui et al. 2014

many Fukui san’s group papers \textsuperscript{(2018)}
Cloud Cloud Collision evidence in Spitzer bubbles

partial arc-like structures of 8 micron
and off-center star formation regions

two velocity components of CO with $\Delta v \sim 20$ km/s

Fukui et al. 2014
CCCs Simulation


1. $0.21 \times 10^{-1}$, $27.00$, $N=4300$

2. $0.31 \times 10^{0}$, $907.00$, $N=4300$

3. $0.51 \times 10^{0}$, $1871.00$, $N=4300$

4. $0.60 \times 10^{0}$, $3339.00$, $N=4300$

Gravitationally unstable
Cloud-Cloud Collisions

a trigger of high mass star formation?

- High Density Region

High Mass Cores?
 CCCs simulations

- Stone 1970
- Nittmann 1981
- Gilden 1984
- Lattanzio + 1985, 1988
- Nagasawa & Miyama 1987
- Habe & Ohta 1992
- Anathpindika 2010
- Inoue+ 2013, 2018
- Takahira + 2014, 2018
- Wu+ 2015, 2017
- Whitworth+ 2018
2. cloud cloud collision rate ?

- two estimates of collision time scale of GMCs
  
  a) \( \tau_{col} \sim 240 \text{Myr} \)  
  for random clouds with \( \sigma_{\text{cloud}} \sim 10 \text{km/s} \)  
  e.g. McLeod 2012

  b) \( \tau_{col} \sim 10 - 30 \text{Myr} \)  
  from GMCs simulations of galaxy scale

- Tasker and Tan 09, Tasker 11
  
  Fujimoto et al. 14ab, Dobbs et al. 15
CCC\textsuperscript{s} in a galaxy

molecular cloud simulations of a whole galaxy

$\rightarrow$ CCC\textsuperscript{s} are frequent enough for massive star formation in our Galaxy (Tan 2000)
clouds in the simulation

mass size relation

(a)

Fujimoto et al. (2014a)

cloud life time

collision rate ~ 1/t_col

Type A
Type B
Type C

Figure 8.
star formation rate estimation

collision time scale \( \tau_{\text{coll}} \sim 10 - 30 \text{Myr} \)

cloud number \( N_{\text{cl}} \)

collision rate \( \dot{N}_{\text{coll}} \sim f_{\text{col}} N_{\text{cl}} / \tau_{\text{coll}} \)

SF rate by CCCs
\[
\dot{M}_{sf} \sim \varepsilon_{sf} M_{\text{cl}} \dot{N}_{\text{coll}} \sim \frac{\varepsilon_{sf} f_{\text{col}}}{0.01} M_{\text{sun}} / \text{yr}
\]

collision frequency is high enough for star formation rate
3. Cloud Cloud Collision simulation

collision of turbulent clouds with different sizes

Takahira et al. 2014
Takahara et al. 2018
Our Simulation

Takahira et al. (14, 18)

- Turbulent clouds (Larson) collisions
- 3D Hydrodynamic AMR code (ENZO)
- High resolution: $\Delta l \geq 0.014 \text{pc}$
- Radiative cooling
- Self-gravity

no MHD

Habe & Ohta (92)
Cloud Model

Table 1. Initial cloud model parameters.

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
<th>Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_c \ (M_\odot)$</td>
<td>7613</td>
<td>14935</td>
<td>26722</td>
<td>20398</td>
</tr>
<tr>
<td>$r_c \ (pc)$</td>
<td>14.4</td>
<td>20.9</td>
<td>28.0</td>
<td>10.0</td>
</tr>
<tr>
<td>$\bar{n} \ (cm^{-3})$</td>
<td>24.47</td>
<td>15.94</td>
<td>11.86</td>
<td>120.4</td>
</tr>
<tr>
<td>$\sigma_v \ (km \ s^{-1})$</td>
<td>2.62</td>
<td>3.17</td>
<td>3.57</td>
<td>3.01</td>
</tr>
<tr>
<td>$T_{BE} \ (K)$</td>
<td>480</td>
<td>720</td>
<td>960</td>
<td>700</td>
</tr>
<tr>
<td>$t_{ff} \ (Myr)$</td>
<td>10.4</td>
<td>13.0</td>
<td>15.0</td>
<td>4.71</td>
</tr>
<tr>
<td>$k \ mode$</td>
<td>5–12</td>
<td>10–19</td>
<td>10–25</td>
<td>8–16</td>
</tr>
</tbody>
</table>

collision velocity

$v_{col} = 5, 10, 20, 30 km/s$
Probability Density Function (PDF)

Probability distribution functions (PDF) for the cloud collisions at different relative velocities. The blue dashed line shows a log-normal fit. Top-left shows the comparison static case for the gas in Cloud 2 when it does not undergo a collision. The black solid line depicts the profile at 1.0 Myr while the red dotted line is the gas at $t = 5.3$ Myr. The high density gas maintains a log-normal fit over the duration of the simulation. Top-right shows the result for the 3.0 km/s collision case, bottom-left the 5.0 km/s and right the 10.0 km/s simulation. In all three cases, the black solid line shows the profile when the maximum number of cores are present. Upon forming the cores, the gas deviates from the log-normal to grow an extended tail.

In all simulations, core formation at our main threshold density (red dashed) and at the lower threshold value (black solid) begins at a time much shorter than the free-fall time of Cloud 1 or Cloud 2 ($t_{ff} \approx 0.7 t_{ff}$), ruling out the possibility of core production purely from the cloud's natural gravitational collapse. Initially, a small number of short-lived cores are formed. The time for the first core formation and the peak in the maximum number of cores is dependent on collision velocity, with a higher relative speed creating cores more rapidly. For our threshold density, cores begin to form at $0.4 t/t_{ff}$ in the 3 km/s simulation which is reduced to $\sim 0.18$ in the 5 km/s collision and 0.1 in the 10 km/s collision. The time for the maximum core number reduces from $\sim 0.7, 0.5$ to 0.25 as we increase collision speed. In the case of the two lower core thresholds, the increase in velocity also corresponds to a higher maximum core count, with three times as many cores formed at the lowest threshold in the 10 km/s run compared with the blue line.

$\log \rho$ (g/cm$^3$)

$\text{blue line : log normal supersonic turbulence PDF}$

$$f(\rho) = \frac{A}{\sqrt{2\pi\sigma^2}} \exp \left( -\frac{(\ln(\rho/\bar{\rho}) - \mu)^2}{2\sigma^2} \right)$$

Padoan + 1997, Federrath + 2008
Small-Large clouds

ENZO code

10km/s

$7 \times 10^3 M_\odot$  $2 \times 10^4 M_\odot$

White : cores  $\rho > 10^{-19} \text{ [g/cc]}$
Red : bound cores  (Gravitational E. + Internal E. < 0)
change of PDF in colliding clouds
power law tails

Figure 6. Core formation inside the shock front during the collision. Gas initially collapses to form filaments that predominantly follow an arched shape of the shock. These then fragment into cores which then accrete gas from the surrounding filament before potentially interacting and merging with neighbouring cores. This figure is taken from the 10 km/s collision between the Large and Medium clouds. The time for each frame is $t/t_{\text{ff,M},\text{max core number}} = 0.51$ (left), 0.7 (middle, at maximum core number) and 0.71 (right).

Figure 7. Probability distribution functions (PDF) for the Medium and Large cloud collisions at convergence point with different relative velocities. The black solid line shows the profile for each run at the point of final core number while the blue dashed line shows a log-normal fit. Top-left plot shows the result from the 5 km/s collision case, top-right is for the 10 km/s, bottom-left is from 20 km/s and bottom-right is the 30 km/s simulation. In all cases, the gas deviates from the log-normal profile to form an extended tail as cores form.

Figure 8. The cumulative mass distribution (CMF) for the collision between Medium and Large Cloud at different collision velocities. The distribution is plotted at the point of final core number. The panels show the collision at 5 km/s (top-left), 10 km/s (top-right), 20 km/s (bottom-left) and 30 km/s (bottom-right). The black triangles mark the core masses while the red dashed line shows the fit $N_{\text{core}} = 300 M^{-0.6}$, giving a value of $\gamma = 1.6$ for Equation 4 in agreement with the observed value for the Orion molecular cloud Tatematsu (1993). In the 5 km/s collision, the CMD is well fitted by the red dashed line between the mass range of $3 M_\odot < M < 1100 M_\odot$, but higher collision speeds, the CMD bends away from the fit at increasingly lower masses.
Core Number Evolution

5km/s  10km/s  20km/s

density threshold for core definition:

\[ 1 \times 10^{-20} \text{gcm}^{-3} \]
\[ 5 \times 10^{-20} \text{gcm}^{-3} \]
\[ 1 \times 10^{-19} \text{gcm}^{-3} \]
\[ 5 \times 10^{-19} \text{gcm}^{-3} \]

shock compression forms cores but, less dense cores destroyed in high speeds mass and density of core increases via gas accretion (M-L model)
Cumulative Core Mass Function

\[ \rho_{th} = 10^{-19} \text{g/cm}^3 \]

\[ \frac{dN}{dM} \propto M^{-\alpha} \]

\[ \alpha = 1.6 \]

(molecular cores, Tatematsu+ 93
Kramer+ 98)

\[ \alpha = 2.3 \]

Salpeter (1955)

(prestellar cores, Ikeda+ 97
Kramer+ 98)

Core mass ranges in \( M > 10 \text{ M}_{\odot} \),
for \( v > 10 \text{ km/s} \)

(M-L Model)
The power-law tail in the denser gas than 10$^{−5}$M$_{\odot}$.

The maximum core number, the core number at the convergence point, means that gas accretion does not continue long enough for the CMDs to be fitted with a power-law of index $−1$. The power-law tail of the core number shown in figure 5 is much smaller than those at 10–30 km s$^{−1}$, showing that the maximum core number is the small extension of the power-law tail in the Medium–Large case for 20 km s$^{−1}$.

As in the previous simulation, we give the collision speed $v$ and the free-fall time ($t_{ffc}$) for more than 1 Myr after the converging point, such that the collision events at 20 km s$^{−1}$ can support the Constant cloud for more than 1 Myr. The mass of the bending point is much larger than the Medium–Large case for 20 km s$^{−1}$.

The typical collision speed between Cloud1 and Cloud2 is 10 km s$^{−1}$, that are in the speed range $10^{−5}$–$10^{−1}$ km s$^{−1}$, and $10^{+1}$–$10^{+3}$ km s$^{−1}$.

The mean cloud collision time scale is the mean time taken to reach the maximum number of cores, which is the mean cloud collision time scale. Tan ($\epsilon$) showed in figure 11 gives the time taken to reach the maximum number of cores defined by the four threshold density cases. The power index of the cumulative core mass distribution in the range greater than the bending point is identical for more than 1 Myr after the converging point, such that cloud–cloud collisions contribute well to the gravitational unstable mass.

To explore the effect of the initial cloud structure, we simulated collision between a compact cloud with a constant density and a medium cloud of length scale 0.046. We also add turbulent velocity fields.

For more details, see Takahira + 2018.
break point in obs. CMD
high speed CCC evidence?

Tsuboi et al. 2015
summary

- CCCs are a strong candidate of trigger of high mass SF
- CCCs are frequent in galaxy scale simulations
- dense cores form in colliding clouds
- core mass ranges $M > 10M_{\text{sun}}$ for $v > 10$ km/s
- core mass function is the power law form with break
- the break depends on collision speed, and colliding clouds’ size and mass