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The formation of young massive clusters via cloud-cloud collisions

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Young massive star clusters (YMCs) abundant in interacting galaxies, are **young** (< 100 Myr) yet **massive** and **dense** (> 10^4 $M_\odot$ within a few pc).

The unusually high star formation rate of YMCs is a mystery on how they are formed.

Why do we study YMCs?

- To test our current star formation theory
- To understand the formation of galaxies
- To investigate the origin of globular clusters

Image Credit: NASA/ESA

We investigate the formation of YMCs via cloud-cloud collisions, as this mechanism agrees with the observed hierarchical formation and reduces their formation timescale. Cloud-cloud collisions are frequent in highly dynamic galactic environment, e.g. spiral arms. Our aim is to explore the parameter space for the formation of YMCs via colliding clouds, starting with the collision speed, initial cloud density, and turbulence.

We perform colliding clouds simulations using PHANTOM, an SPH code.

The collision is head-on and along the elongated axis. We use 5 million particles as resolution and the isothermal equation of state. Sink particles are introduced to replace high density regions, so each of them is a placeholder for small group of stars. Our parameter range chosen from observations:

- Relative collision velocity: 0 – 50 km s^{-1}
- Initial cloud density: 130 – 518 cm^{-3}
- Turbulence: 2.5 – 5 km s^{-1}

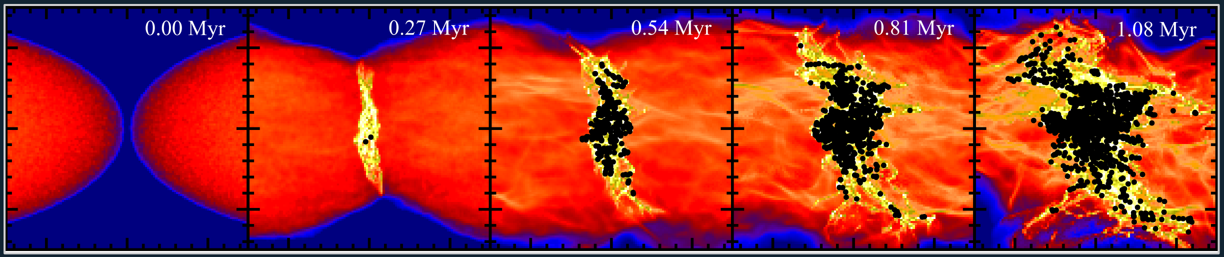

Fig 1: The formation of YMC in one of the colliding clouds simulations with relative velocity of 25 km s^{-1}, initial cloud density of 250 cm^{-3}, and turbulence of 2.5 km s^{-1}. Each box size is 7x7 pc^2.

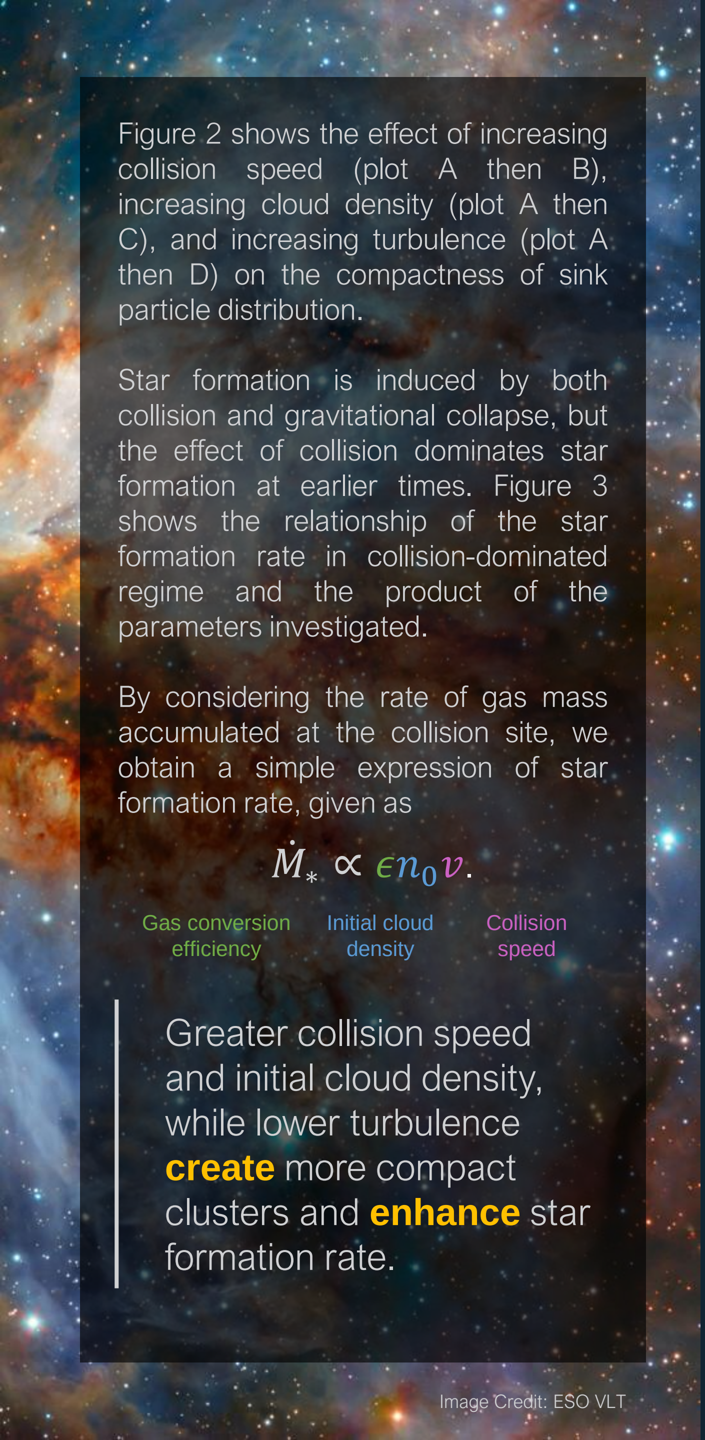

Figure 2 shows the effect of increasing collision speed (plot A then B), increasing cloud density (plot A then C), and increasing turbulence (plot A then D) on the compactness of sink particle distribution.

Star formation is induced by both collision and gravitational collapse, but the effect of collision dominates star formation at earlier times. Figure 3 shows the relationship of the star formation rate in collision-dominated regime and the product of the parameters investigated.

By considering the rate of gas mass accumulated at the collision site, we obtain a simple expression of star formation rate, given as

$$\dot{M}_* \propto \epsilon n_0 v.$$

Gas conversion efficiency

Initial cloud density

Collision speed

> Greater collision speed and initial cloud density, while lower turbulence **create** more compact clusters and **enhance** star formation rate.

Image Credit: ESO VLT

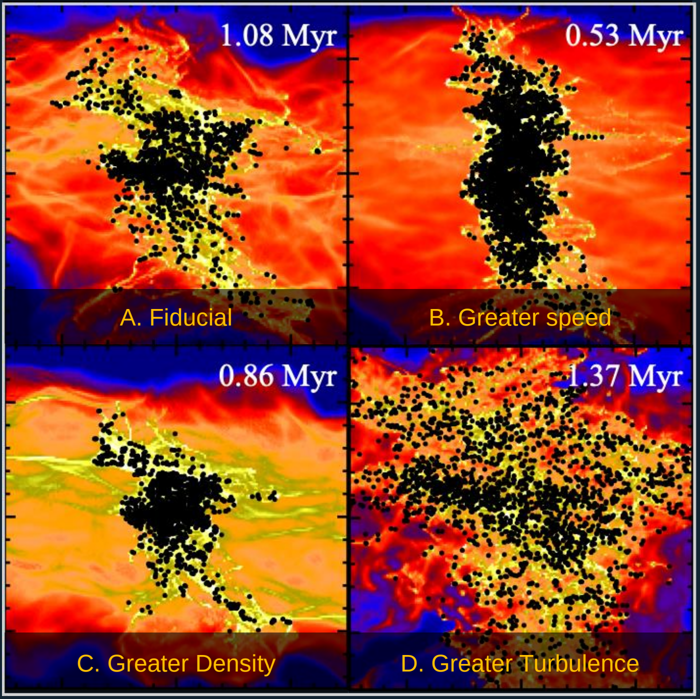

Fig 2: The sink particle distribution in different collision models at $t_{10\%}$, the time when 10% of gas mass is converted into sinks. Each box size is 7x7 pc^2. Greater speed, greater density, and lower turbulence generally create more compact clusters at a shorter timescale.

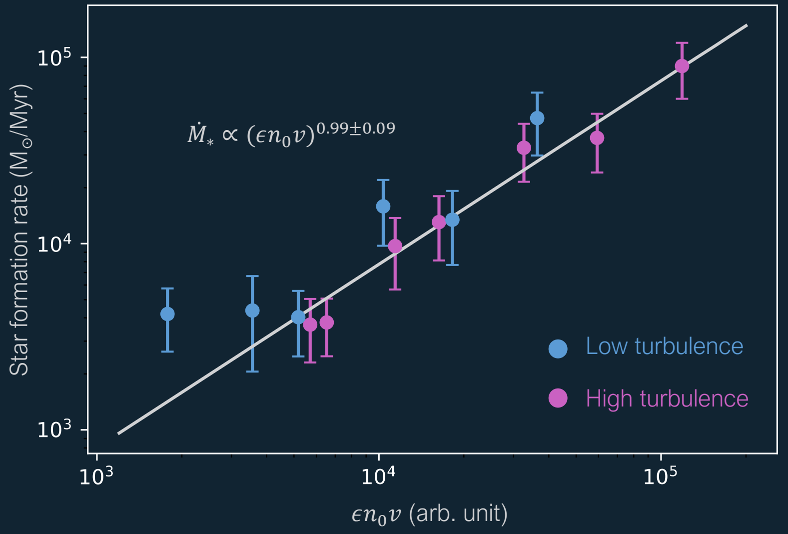

Fig 3: The relationship of overall star formation rate and the product $\epsilon n_0 v$ parameter. The gas conversion efficiency, taken from Krumholz & McKee (2005), is given as

$$\epsilon \propto (\text{virial ratio})^{-p} (\text{turbulence})^{-q}.$$

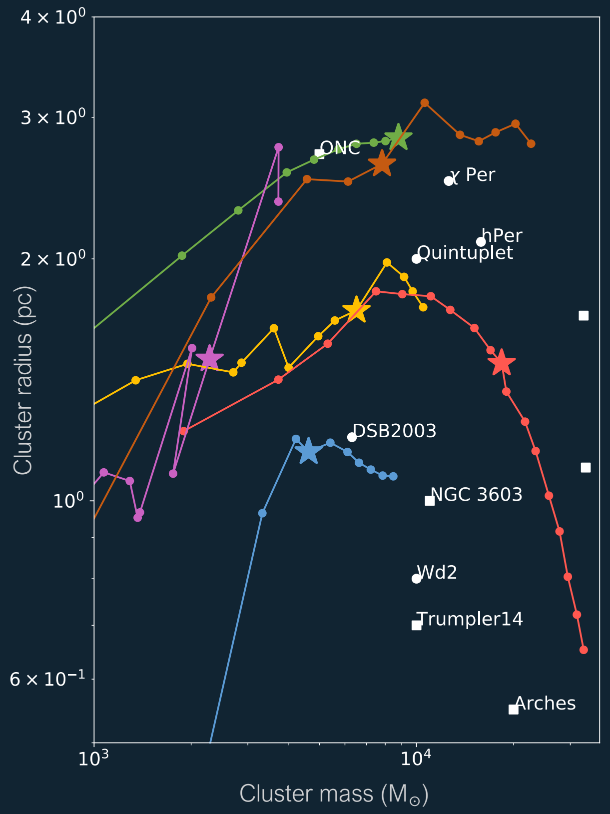

Fig 4: Evolutionary tracks of the massive clusters identified using DBSCAN in radius-mass plot.

We use DBSCAN, a clustering algorithm to identify massive clusters. Figure 4 shows their evolutionary tracks in the radius-mass plot. With relative collision velocity ≳ 25 km/s, initial cloud density ≳ 250 cm-3, and turbulence ≈ 2.5 km/s, **our models are able to form clusters that resemble the YMCs in Milky Way within 1 Myr.**

Road to Stellar Feedback

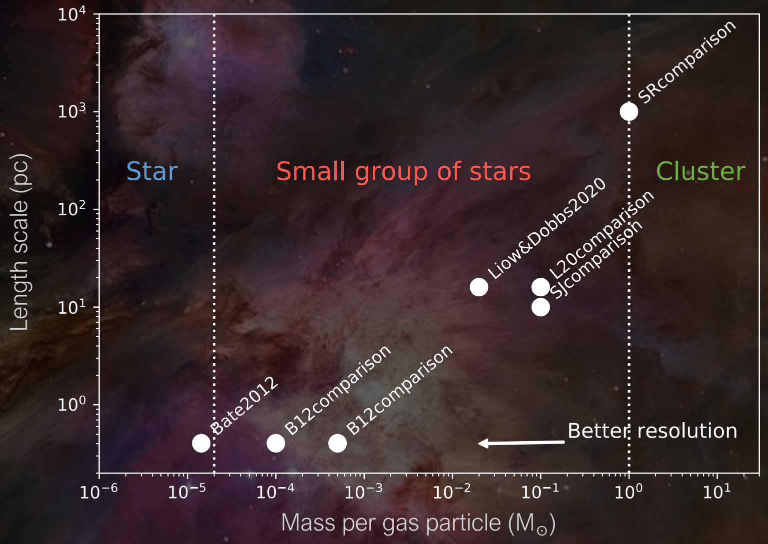

Fig 5: The length scale vs gas mass in original & our models.

Feedback is expected to play a significant role at a later time (> a few Myr) in suppressing/enhancing star formation and thus massive cluster formation. **However, in order to model stellar feedback, we need individual stars rather than large sinks.** If each sink is considered as small group of stars or a cluster as shown in Figure 5, then the sink mass can be used to sample the initial mass function (IMF).

We introduce **grouped star formation**, whereby sinks are firstly grouped according to their positions, velocities, and ages, then the group masses are used to sample the IMF and form stars. This method is the most useful when each sink is considered a small group of stars. The models are performed using Ekster in AMUSE.

Image Credit: NASA/ESA

We show here one of our comparisons. We use grouped star formation on low resolution isolated cloud cluster simulations and compare the results with the original simulation by Bate (2012). As shown in Figure 6, by choosing suitable grouping parameters, our method can sample a complete Kroupa IMF and works better than simply forming a population of stars from each sink (‘no grouping’). In addition, other properties like the stellar distribution and velocity dispersion of the stars can be similar to the original simulation.

We also use this method in parsec-scale isolated cloud cluster simulation, parsec-scale colliding cloud simulation, and kiloparsec-scale spiral arm simulation. Using this method, we are one step closer to modelling stellar feedback in colliding clouds system.

> We find that grouped star formation is **robust** in simulations of different length, speed, and time scales

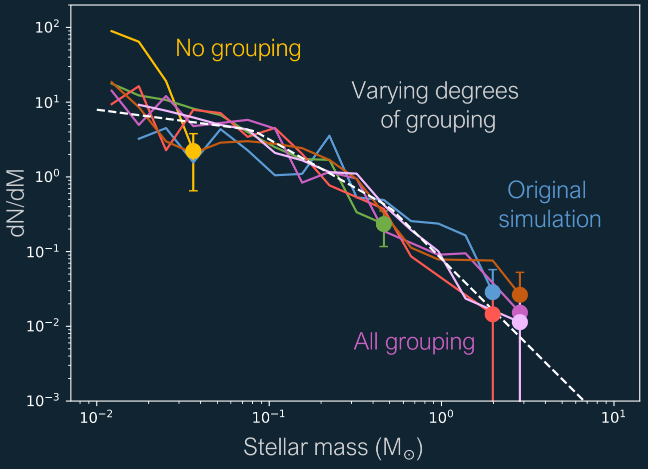

Fig 6: The IMFs of the original simulation and our models of varying degrees of grouping.

Additional physics

To ensure a more realistic colliding clouds model, additional physics can be included. Some investigation by existing literature are:

Collision kinematics

- Star formation rate depends on the amount of gas concentrated at collision site, but the morphology of the clusters may change.

Magnetic field

- Star formation is suppressed strongly when the magnetic field is perpendicular to the collision.

References

Main work:
- Liow & Dobbs (2020)
- Liow, Rieder, Dobbs & Jaffa (in prep.)

Non-exhaustive list:
- Bate (2012)
- Dobbs, Liow & Rieder (2020)
- Dobbs & Wurster (2021)
- Fukui et al. (2021)
- Krumholz & McKee (2005)
- Longmore et al. (2014)
- Walker et al. (2016)
- Wall et al. (2019)

Software

PHANTOM: Price et al. (2018)
AMUSE: Portegies Zwart & McMillan (2018)
Ekster: Rieder et al. (in prep.)

THANK YOU!

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