ENVIRONMENTAL EFFECTS ON THE DYNAMICAL EVOLUTION OF STAR CLUSTERS IN TURBULENT MOLECULAR CLOUDS

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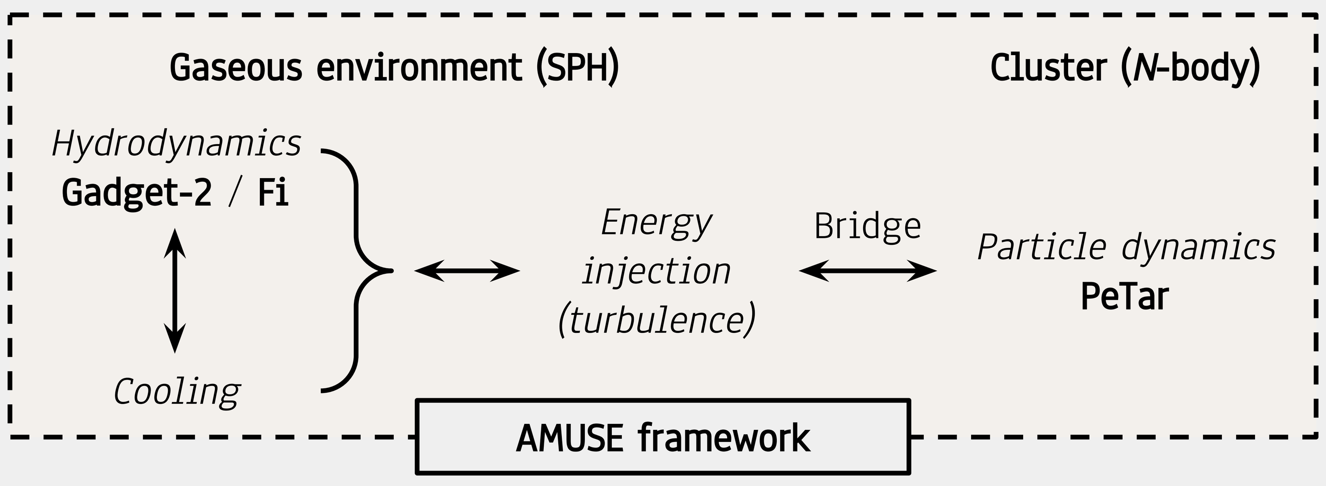
We focused on the interplay between the internal cluster stellar dynamics and the external perturbations caused by its parent cloud turbulence. We conducted a series of simulations following simultaneously the dynamical evolution of the cluster and the hydrodynamics of the background. Comparing our simulations to the control runs, we found that when both the processes are included they couple in a complex fashion. Evidence of the coupling was found studying the mass lost by the cluster throughout the simulations and the outer density distribution of the cluster. Moreover, in agreement with one of the few published studies of the scenario, we found that the tidal field generated by the turbulent structures accelerates its internal evolution, and the cluster undergoes core collapse more rapidly.

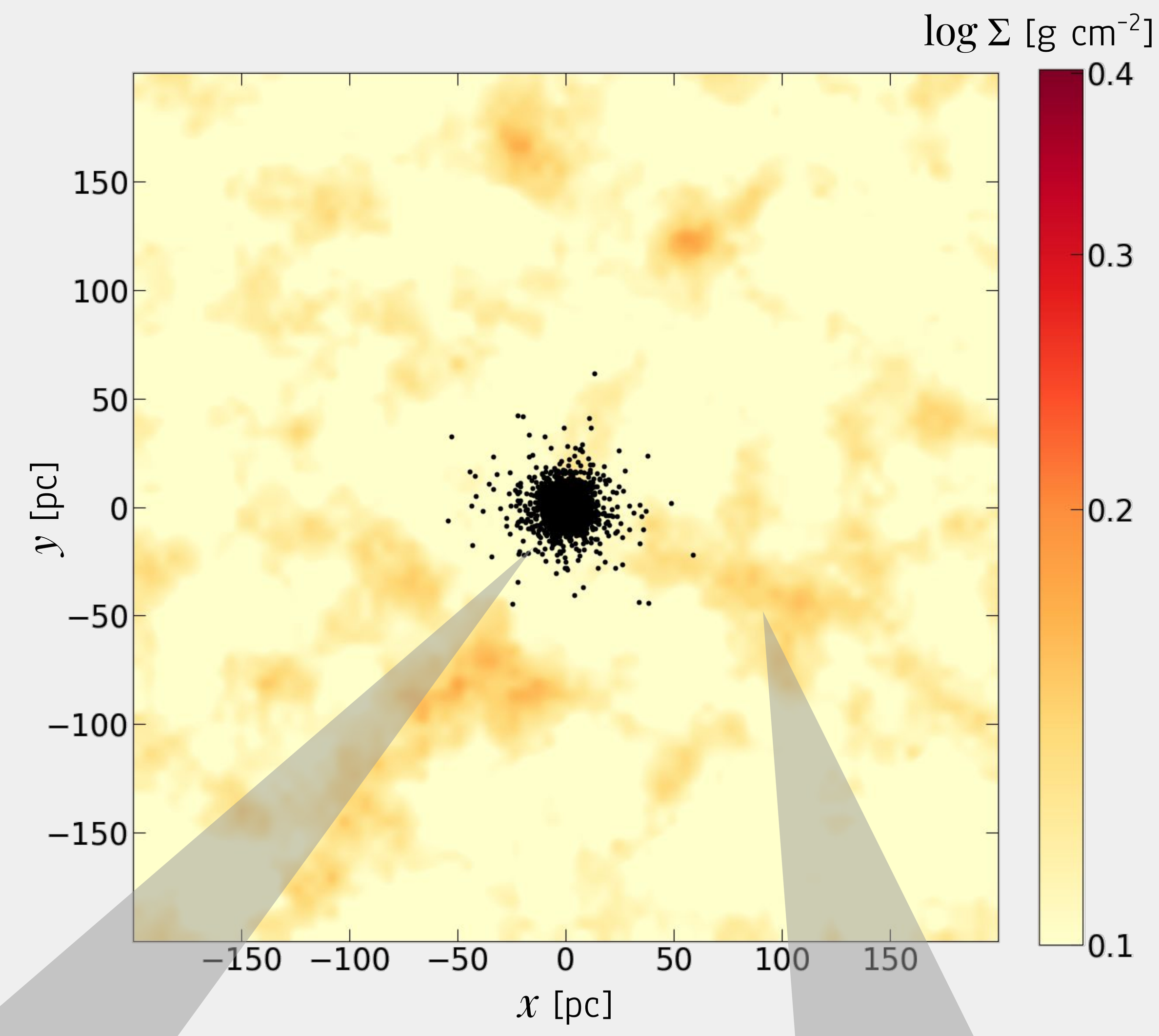
NUMERICAL METHODS

We followed the evolution of the system with the smooth particle hydrodynamics (SPH) codes **Gadget-2** (Springel 2005) and **Fi** (Gerritsen & Icke 1997; Pelupessy et al. 2004) for the gaseous environment, and the *N*-body code **PeTar** (Wang et al. 2019) to handle stellar dynamics. The two codes interacted through the **Bridge** routine within **AMUSE** (Astronomical Multipurpose Software Environment; Portegies Zwart et al. 2009; Portegies Zwart 2018). Hence, while evolving, the star cluster felt its own gravity and the fluctuating potential generated by the dense, evanescent structures in the turbulent cloud. For a more realistic gaseous background, we implemented two routines to mimic its thermal behaviour and gradually developed the turbulent field.



INITIAL CONDITIONS

Turbulence in the gas is gradually developed using a driving wavelength, k, and a velocity dispersion, $V_{\rm rms}$, that resemble the observed star-forming complexes. Once it reached a steady-state, we inserted the cluster at the centre of the periodic box, and evolved the system for approximately 100 Myr. To study how the environment affects the clusters with different properties, we repeated the runs using various stellar densities and initial mass functions (IMFs).



STAR CLUSTER

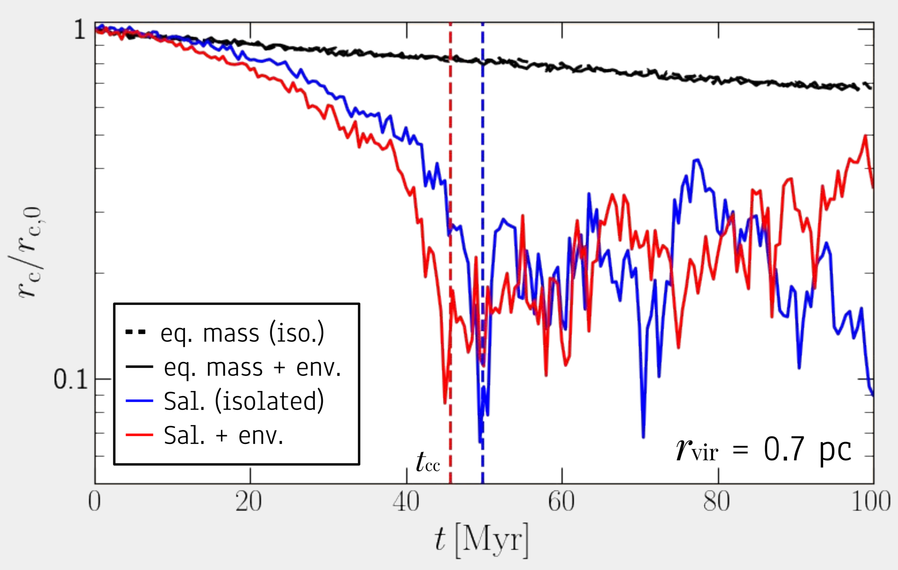
Model: Plummer (1911)
Size: $r_{\rm vir}$ = 0.7, 1.3 or 3.0 pc
Mass: $M_{\rm tot} = 10^4\ M_\odot$ with equal mass stars, Kroupa (2001) or Salpeter (1955) IMF

ENVIRONMENT

Number density: n = 10 cm^{-3}
Periodic box size: L = 400 pc
Velocity dispersion: $V_{\rm rms}$ = 15 km s^{-1}
Driving wavenumber: $4 \le k_{\rm kick} \le 8$

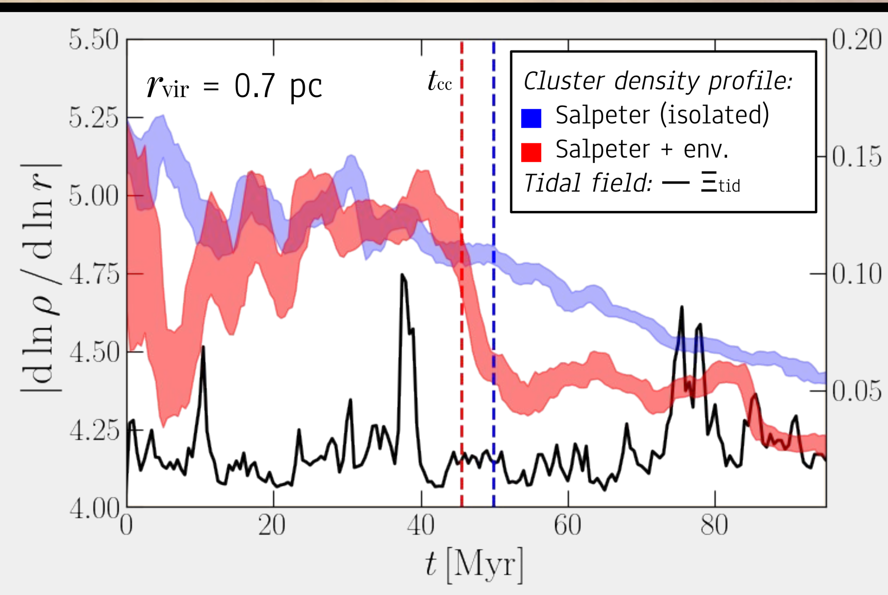
RESULTS: CORE EVOLUTION

Tidal harassment from the external structures accelerates the cluster evolution. The core radius, r_c, shrinks faster, leading to earlier core collapse (dashed vertical lines). This supports, e.g., the results from Gnedin et al. (1999), who found a similar behaviour simulating globular clusters evolving near the Galactic centre.



RESULTS: OUTER REGION

The evolution of the outer density profile of the harassed clusters departs significantly from isolated systems. Collisions with the background clouds abruptly modify the cluster shape. By the end of the simulation, the imbedded clusters display a sparser configuration than their respective reference isolated runs.



RESULTS: CLUSTER MASS LOSS

Clusters with an IMF lose more stars rapidly because of their faster dynamical evolution. External structures further accelerate mass loss by stripping stars. Our models show, however, that the mass lost from the harassed clusters is higher than can be accounted for in the control equal mass simulations. This indicates a coupling between these two processes.

Cluster model			% $M_{\rm lost}$ at t = 95 Myr		
$r_{\rm vir}$ (pc)	IMF	range ($M_\odot$)	isolated cluster	cluster + env.	cluster+env. *(eq. mass)*
0.7	Sal	[0.1; 3]	1.78	2.47	0.14
0.7	Sal	[0.1; 6]	3.25	3.66	
1.3	Sal	[0.1; 3]	0.24	0.46	0.26
1.3	Sal	[0.1; 6]	1.02	1.73	
1.3	Kr	[0.1; 3]	0.32	0.77	
1.3	Kr	[0.1; 6]	1.22	1.47	
3.0	Sal	[0.1; 3]	0.15	1.73	1.64
3.0	Sal	[0.1; 6]	0.18	1.89	

The highlighted model is shown in the plots (above).

DISCUSSION

Our work is intended to show that even simple models have observational consequences and to provide insights regarding the interplay between the dynamical evolution of star clusters and their gaseous background. The mechanisms studied here will impact the evolution of the cluster and will only be magnified by achieving more physical models.

Our choice of initial conditions allows us to avoid some more complex stages of clusters formation that a more physical model would require. We are aware that stellar evolution plays a significant role when including younger stars with higher masses, and the feedback mechanisms acting in such environments are complicated and still far from completely understood.

We defined the variable

$$\Xi_{\rm tid}(t) \equiv \sqrt{\Xi_{\alpha\beta}(\boldsymbol{x}_{\rm c}, t)\Xi_{\alpha\beta}(\boldsymbol{x}_{\rm c}, t)} \quad \text{with} \quad \Xi_{\alpha\beta}(\boldsymbol{x}_{\rm c}, t) \equiv -\frac{\partial^2 \phi}{\partial x_\alpha \partial x_\beta}(\boldsymbol{x}_{\rm c}, t)$$

computed at the cluster core centre, $\boldsymbol{x}_{\rm c}$, to represent the tidal field acting on the cluster. Here, $\phi(x, t)$ is the gravitational potential per unit mass generated by the gas at time t.

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