Constraining the star formation efficiency by properties of tidal tails

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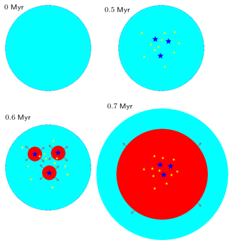
Initial conditions in young star clusters

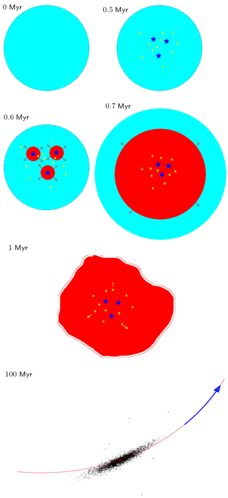
- What is the star formation efficiency ($\mathrm{SFE} = M_{\mathrm{cl}}(0)/(M_{\mathrm{cl}}(0) + M_{\mathrm{gas}}(0))$) ?
- On what time-scale is the natal gas expelled?
- Adiabatic gas expulsion ($\tau_{\mathrm{M}} \gg t_{\mathrm{h}}$) is different from impulsive gas expulsion ($\tau_{\mathrm{M}} \lesssim t_{\mathrm{h}}$) because the former conserves adiabatic invariants.
- Aiming at the origin of young star clusters (in situ SF with gas expulsion, Kroupa+ 2001; conveyor belt model, Longmore+ 2014).

The numerical model



- In the spite of many brave attempts, hydrodynamic simulations contain many uncertain parameters $\rightarrow$ we resort to N-body simulations (stars are directly integrated but gas is only roughly approximated by an analytic time-dependent spherically symmetric model).
- The cluster forms at the centre of an infrared dark cloud.
- Feedback from massive stars cleans the cloud of its natal gas.

The numerical model



- As the natal gas gets expelled, its gravitational potential shallows, which unbinds some stars from the cluster.
- The unbound stars continue orbiting the Galaxy forming tidal tail around the cluster on the timescale of $\sim 100\,\mathrm{Myr}$. This is **Tail I**.
- After gas expulsion, the exposed cluster evolves stellar dynamically releasing stars mainly by gradual evaporation (**Tail II**).

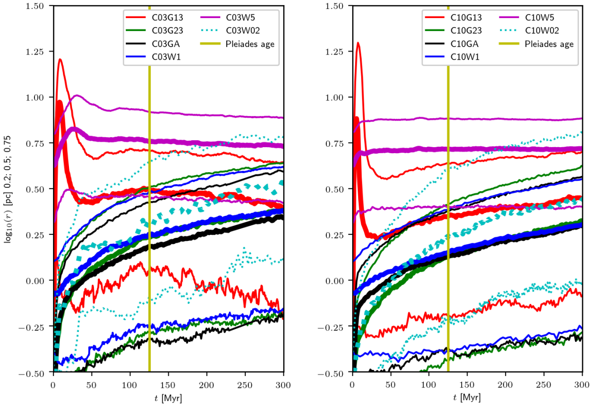
The questions we address

- Inverse analysis where we vary the SFE, τ_{M}, and cluster mass.
- How do the properties of the tidal tail (its extent, thickness, number of stars, ...) depend on the gas expulsion scenario?
- Tail I has not been searched for yet $\rightarrow$ I cannot tell you today how clusters do form, but how their tidal tails are likely to look like for various assumptions about their formation (details of gas expulsion).

The numerical approach

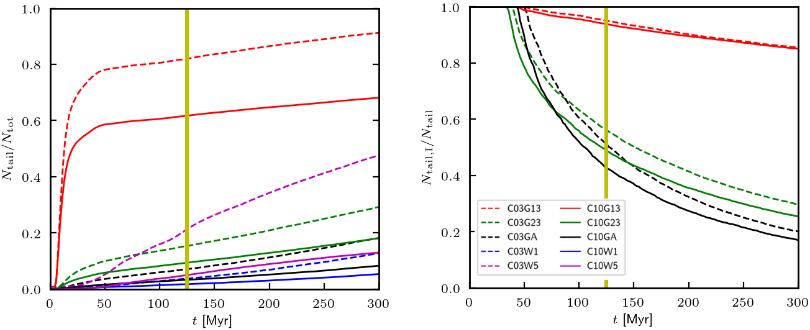
- Nbody6; Plummer model for the cluster and natal gas.
- Star cluster population: $N = 3000$ and $N = 10000$.
- The cluster orbits around the Galaxy, galactic potential consisting of three components: central part, disc and halo. Important periods $2\pi/\omega = 237\,\mathrm{Myr}$, $2\pi/\kappa = 168\,\mathrm{Myr}$, $2\pi/\nu = 68\,\mathrm{Myr}$.
- Gaseous potential, $M_{gas}(t) = M_{gas}(0)\exp\left(-(t - t_d)/\tau_M\right),\ t > t_d$.
- List of performed models:
  - $r_h \simeq 0.2\,\mathrm{pc}$ with $\mathrm{SFE} = 1/3$; $\tau_M = 0.02\,\mathrm{Myr}$ (C03G13 and C10G13)
  - $r_h \simeq 0.2\,\mathrm{pc}$ with $\mathrm{SFE} = 2/3$; $\tau_M = 0.02\,\mathrm{Myr}$ (C03G23 and C10G23)
  - $r_h \simeq 0.2\,\mathrm{pc}$ with $\mathrm{SFE} = 1/3$; $\tau_M = 1.0\,\mathrm{Myr}$ (C03GA and C10GA)
  - $r_h \simeq 1.0\,\mathrm{pc}$ with $\mathrm{SFE} = 1$; (C03W1 and C10W1)
  - $r_h \simeq 5.0\,\mathrm{pc}$ with $\mathrm{SFE} = 1$; (C03W5 and C10W5)

The reaction of the cluster to gas expulsion: cluster Lagrange radii



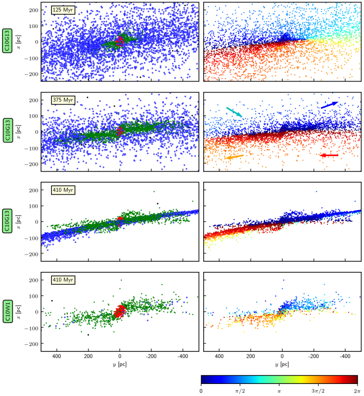
Left panel: Models with $N = 3000$ ($M_{\rm cl} = 1400\,\mathrm{M}_\odot$). Right panel: Models with $N = 10000$ ($M_{\rm cl} = 4400\,\mathrm{M}_\odot$).

The reaction of the cluster to gas expulsion: cluster and tail populations



Left panel: The fraction of the tail stars. Right panel: The fraction of tail I stars in the tail.

Morphology and velocity structure of tail I and tail II



- Gas free model C10W1 forms only tail II (lower row). Tail II is clearly S-shaped and expands from the cluster.
- The tidal tail of model C10G13 is more complex: it forms tail I (blue dots) and tail II (green dots). Its tail II is similar to the tail of model C10W1.
- Tail I oscillates in thickness in the direction x reaching maximum thickness at $\approx 375\,\mathrm{Myr}$, and minimum thickness at $\approx 410\,\mathrm{Myr}$.
- Near the maximum thickness, tail I shows a shear-like motion.
- Tails I and II evolve independently.

Why are tails I and II so different?

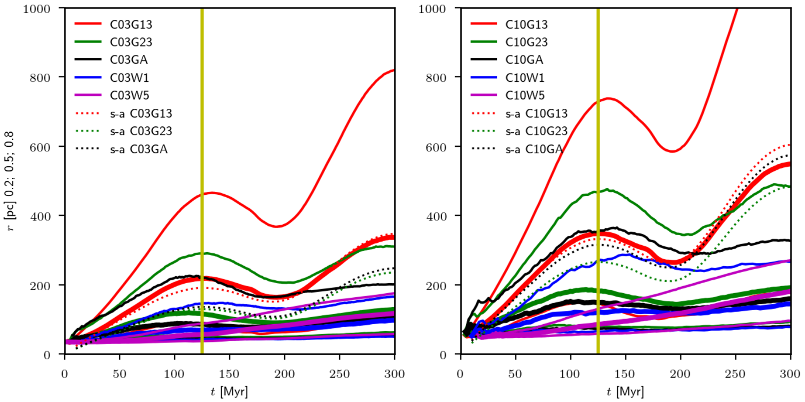
Tail I:

- Stars are released at the beginning of the simulation on time-scale $\ll 2\pi/\kappa$.
- Stars escape at the speed comparable to the cluster velocity dispersion $\rightarrow$ they escape almost isotropically.
- We found a (semi)-analytic model for the minima of tail thickness, tail velocity dispersion and the tail half-mass radius $r_{\mathrm{h,tail}}$ (Dinnbier & Kroupa submitted).
- The minima do not occur periodically, and they are only functions of galactic frequencies ω, κ and ν independent on the cluster properties.

Tail II:

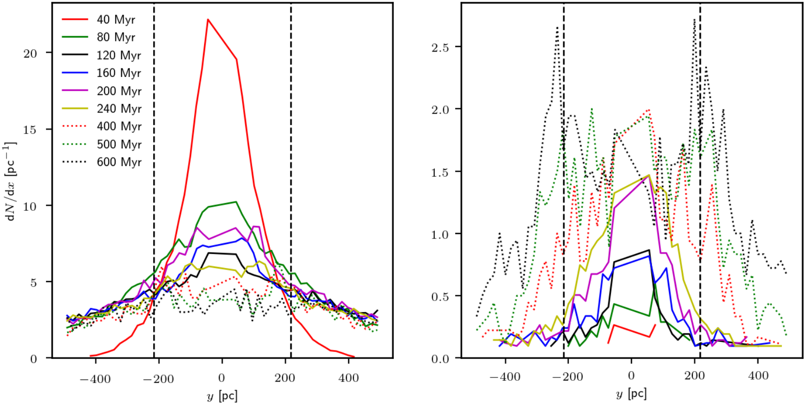
- Stars are released throughout the simulation at approximately a constant evaporation rate ($\sim$ one star per crossing time).
- The escape speed for the majority of stars is smaller that the cluster velocity dispersion $\rightarrow$ they escape preferentially in the vicinity of Lagrange points L1 and L2.
- The formation of tail II and its epicyclic overdensities was studied by Küpper+ 2008 and Küpper+ 2010.

The extent of the tidal tail



Left panel: Lower mass models ($M = 1400\,\mathrm{M}_\odot$). Right panel: Higher mass models ($M = 4400\,\mathrm{M}_\odot$). The semi-analytic solution for $r_{\mathrm{h,tail}}$ is shown by the dotted lines.

The density profile of the tidal tail



Left panel: Cluster with rapid gas expulsion and lower $\mathrm{SFE} = 1/3$ (model C10G13). Right panel: Gas free cluster ($\mathrm{SFE} = 1$; model C10W1).

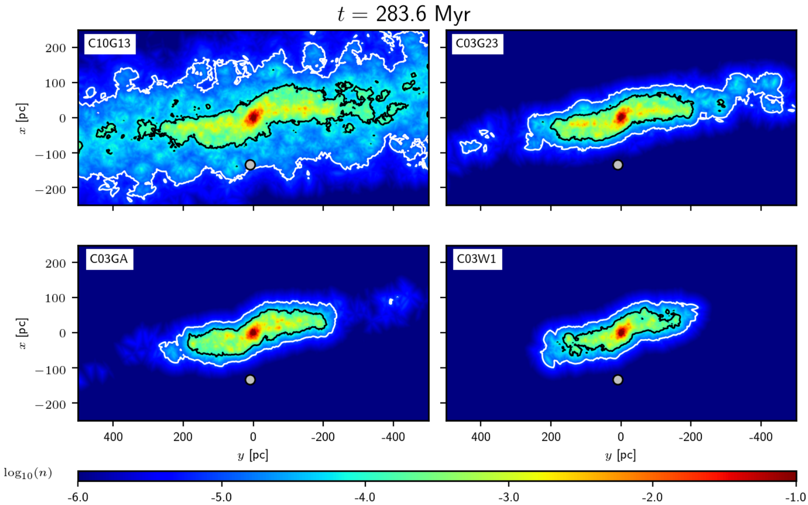
Observational limitations

- **The sensitivity of Gaia (for the final data release):** At the distance to the Pleiades tail, stars earlier than G7 will be measured with position error $\approx 0.5\,\mathrm{pc}$ and radial velocity error of the order of $0.5\,\mathrm{km\ s^{-1}}$ $\rightarrow$ velocity structure of models CG13 could be resolved.
- **Contamination due to field stars:** Based on Besançon model (Czekaj+ 2014); number density contamination $n_{\mathrm{tail}} \approx 7 \times 10^{-8}\,\mathrm{pc}^{-3}$ for A stars, and $n_{\mathrm{tail}} \approx 1 \times 10^{-5}\,\mathrm{pc}^{-3}$ for FGK stars (a lower estimate on contamination).
- **Contamination due to the Hyades-Pleiades stream:** $n_{\mathrm{tail}} \approx 3 \times 10^{-5}\,\mathrm{pc}^{-3}$ for any stellar type (an upper estimate on contamination).

Calibration to the Pleiades star cluster

- Which models evolve to the current state of the Pleiades?
- Parameters of the current Pleiades $M_c = 740\,\mathrm{M}_\odot$; $r_h = 2\,\mathrm{pc}$; $\sigma_{cl} = 0.5\,\mathrm{km\ s}^{-1}$ (Converse & Stahler 2008, Pinfield+ 1998, Raboud & Mermilliod 1998)
- Models with $r_h = 0.2\,\mathrm{pc}$ with lower $\mathrm{SFE} = 1/3$ bracket the observed Pleiades mass ($M_c = 280\,\mathrm{M}_\odot$ and $M_c = 1800\,\mathrm{M}_\odot$), radii and velocity dispersion $\rightarrow$ model CG13 evolving towards the Pleiades had $1400\,\mathrm{M}_\odot < M_c(0) < 4400\,\mathrm{M}_\odot$.
- Model with $r_h = 0.2\,\mathrm{pc}$ with $\mathrm{SFE} = 2/3$ and $M_c = 1400\,\mathrm{M}_\odot$ evolves close to the Pleiades.
- Model with $r_h = 0.2\,\mathrm{pc}$ with $\mathrm{SFE} = 1/3$, slow GE and $M_c = 1400\,\mathrm{M}_\odot$ evolves close to the Pleiades.
- Model with $r_h = 1.0\,\mathrm{pc}$ with $\mathrm{SFE} = 3/3$ and $M_c = 1400\,\mathrm{M}_\odot$ has mass $2\times$ higher than the Pleiades $\rightarrow$ the tidal tail is smaller than predicted by this model.

Tail morphology for the models evolving towards the Pleiades

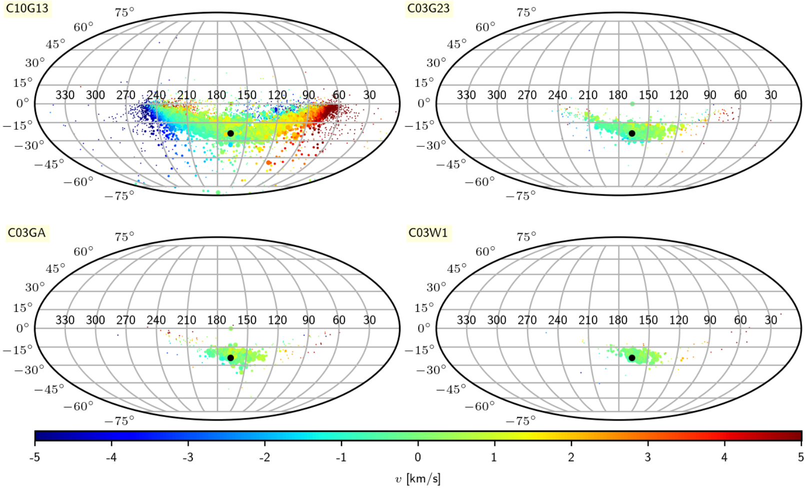


Predictions for the Pleiades

cluster model	$r_{h,tail}$ [pc]	$N_{A,tail,obs}$	MF tail
$\mathrm{SFE} = 1/3$ fast GE	$150\,\mathrm{pc} - 350\,\mathrm{pc}$	$40 - 170$	canonical
$\mathrm{SFE} = 2/3$ fast GE	$100\,\mathrm{pc} - 200\,\mathrm{pc}$	$4 - 11$	canonical
$\mathrm{SFE} = 1/3$ slow GE	$40\,\mathrm{pc} - 100\,\mathrm{pc}$	$1 - 4$	canonical
$\mathrm{SFE} = 1$	$< 20\,\mathrm{pc} - < 90\,\mathrm{pc}$	$< 1 - < 2$	depleted in stars of $m \gtrsim 1\,\mathrm{M}_{\odot}$

The lower and upper bounds are taken from the lower/upper estimate on the field star contamination.

Predictions for the Pleiades

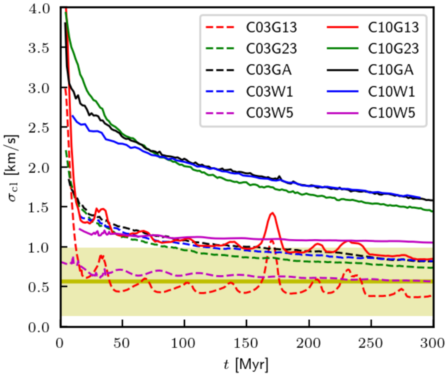


Summary

- The gas expulsion tidal tail has a different morphology from the evaporation tidal tail.
- If the Pleiades formed with $\mathrm{SFE} \lesssim 2/3$ and rapid gas expulsion, they are surrounded by a rich tidal tail (more numerous than the cluster) extending to a distance of $\approx 500\,\mathrm{pc}$, and containing ~ 100 A stars for $\mathrm{SFE} = 1/3$. Some of the stars are even at the Pleiades apocentre, spread all over the sky.
- In this case, the tidal tail of the Pleiades could be easily traced in A stars by the Gaia mission.
- If the Pleiades formed with SFE close to 1, they would be surrounded by a poor and short tail with at most a handful of A stars.
- If the Pleiades formed with $\mathrm{SFE} \approx 1/3$ and adiabatic gas expulsion, the tail does not seem to be discernible from the tail of the model with $\mathrm{SFE} = 1$.

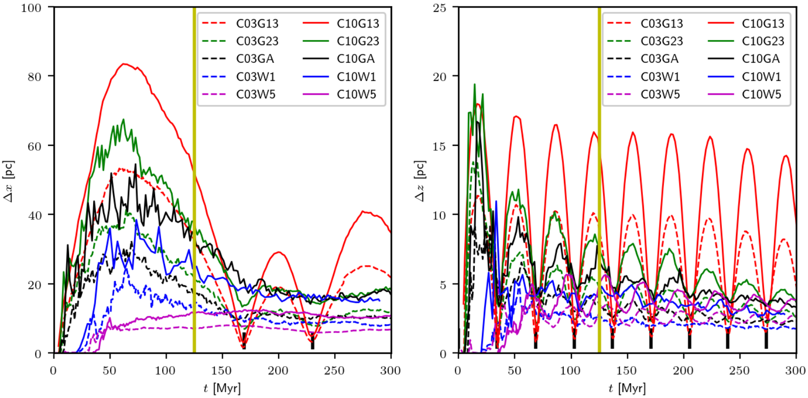
Thank you for your attention

The reaction of the cluster to gas expulsion: cluster velocity dispersion



- Models C03G13 and C10G13 have sharp drop in σ_{cl} after gas expulsion.
- Models C10G23, C10GA and C10W1 have too large σ_{cl} to be precursors to the current Pleiades.
- Models C03G23, C03GA and C03W1 could be precursors to the current Pleiades.

The tail thickness



The tail velocity structure