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The tidal tails of open star clusters produced by early gas expulsion

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Abstract. We investigate, for the first time, the formation and evolution of the tidal tail released from a young Pleiades-like star cluster due to expulsion of primordial gas in a realistic gravitational field of the Galaxy. The tidal tails (as well as clusters) are integrated by NBODY6 from their embedded phase for more than 300 Myr. We vary the star formation efficiency (SFE) from 33% to 100% and the timescales of gas expulsion as free parameters, and provide predictions for the morphology and kinematics of the evolved tail for each of the models. The resulting tail properties are intended for comparison with Gaia measurements, where an inverse analysis of our findings might constrain some of the poorly understood conditions and processes in embedded star clusters during the gas phase and gas expulsion.

Keywords. open clusters and associations: general, open clusters and associations: individual (the Pleiades)

1. Introduction

Young star clusters form as embedded objects within infrared dark clouds, gradually turning the gas into stars. At the same time, the forming massive stars impart the gaseous cloud by powerful feedback, mainly in the form of ionising radiation, stellar winds and radiation pressure. The gas which has not been used for star formation is dispersed by the feedback, cleaning the embedded cluster from its natal gas. This can have significant consequences on the dynamics of the young star cluster depending on the star formation efficiency (SFE), and the gas expulsion time-scale $\tau_{\rm M}$. Here, we use the definition of the SFE as $\text{SFE} = M_{\rm ecl}/M_{\rm gas}(0)$, where $M_{\rm ecl}$ is the total mass of stars formed, and $M_{\rm gas}(0)$ is the mass of the gas present in the star forming volume before star formation commenced.

The duration of $\tau_{\rm M}$ relative to the stellar half-mass crossing time $t_{\rm h}$ determines whether adiabatic invariants of the stellar orbits conserve or not. For adiabatic gas expulsion ($\tau_{\rm M} \gg t_{\rm h}$), the cluster expands gradually and retains the majority of its stars even for an SFE as low as 0.15 (Baumgardt & Kroupa 2007). For impulsive gas expulsion ($\tau_{\rm M} \lesssim t_{\rm h}$), the cluster is generally affected more, and the formation of a bound star cluster is possible only for SFEs higher than ≈ 0.3 (Lada *et al.* 1984). Thus, the details of gas expulsion determine the fraction of stars which are unbound and also the extent of the tail at a given time via the escape velocities. If the cluster survives gas expulsion, it continues losing stars due to its internal cluster dynamics (Küpper *et al.* 2008).

Table 1. List of star cluster models. The embedded clusters are of stellar mass $M_{\rm ecl}$, the initial gaseous mass $M_{\rm gas}(0)$, half-mass radius $r_{\rm h}(0)$. The table also compares the gas expulsion time-scale $\tau_{\rm M}$ with the half-mass crossing time-scale $t_{\rm h}$.

Run name	$M_{\rm ecl}$ [$\rm M_\odot$]	$M_{\rm gas}(0)$ [$\rm M_\odot$]	$r_{\rm h}(0)$ [pc]	$\tau_{\rm M}$ [Myr]	$t_{\rm h}$ [Myr]
C03G13	1400	2800	0.20	0.020	0.028
C03G23	1400	700	0.20	0.020	0.034
C03GA	1400	2800	0.20	1.000	0.028
C03W1	1400	0	1.00	–	0.43
C10G13	4400	8800	0.23	0.020	0.020
C10G23	4400	2200	0.23	0.020	0.023
C10GA	4400	8800	0.23	1.000	0.020
C10W1	4400	0	1.00	–	0.24

In spite of its importance, it is difficult to estimate the SFE and $\tau_{\rm M}$ both observationally (e.g. Lada & Lada 2003) because of its short duration and the difficulty to count all stars formed and all initial gas, and theoretically because of the plethora of physical processes involved (e.g. Dale *et al.* 2014; Gavagnin *et al.* 2017), with some of the works often providing contradictory results.

In this work, we address the question of the SFE and gas expulsion time-scale $\tau_{\rm M}$ as an inverse problem in a stellar dynamical system. We treat the SFE and $\tau_{\rm M}$ as free parameters, and calculate not only the dynamics of a star cluster, but also of its tidal tail in a realistic potential of the Galaxy; each parameter pair of (SFE, $\tau_{\rm M}$) forms a tidal tail, but at a given time, the tidal tails are generally different for different parameter pairs. We tailor the initial conditions to reproduce the present day Pleiades star cluster. This approach circumvents many of the uncertain assumptions encountered in hydrodynamic simulations. We expect that the Gaia mission will reveal the tidal tail around the Pleiades, which should enable to constrain the SFE and gas expulsion time-scale which the Pleiades experienced in their embedded stage.

2. The parameter space

We use two initial cluster masses $1400\,\rm M_\odot$ and $4400\,\rm M_\odot$, with which we explore the following scenarios of gas expulsion:

- Rapid gas expulsion and SFE = 1/3 (models C03G13 and C10G13; see Table 1)
- Rapid gas expulsion and SFE = 2/3 (models C03G23 and C10G23).
- Adiabatic gas expulsion and SFE = 1/3 (models C03GA and C10GA).
- Gas free clusters (models C03W1 and C10W1).

The clusters are integrated with the code NBODY6. The gaseous potential is approximated by a Plummer sphere, which exponentially decays on the time-scale of $\tau_{\rm M}$ after a delay time of 0.6 Myr (Kroupa *et al.* 2001). The clusters move on circular orbits about the Galaxy, which is represented by a realistic gravitational potential of Allen & Santillan 1991. In order to obtain better statistics, we perform 13 (4) different simulations of the lower (more massive) clusters; the results below are average over their realisations.

3. The properties of tidal tails for different gas expulsion scenarios

The fraction of the stars in the tail relative to all stars in the system $N_{\rm tot}$ is shown in the left panel of Fig. 1. Clusters with rapid gas expulsion and low SFE of 1/3 form very populous tidal tails (solid lines), which contain, after ≈ 20 Myr, even more stars than are in the clusters. The number of tail stars rapidly decreases as the SFE increases to 2/3 (dashed lines). Although the clusters with adiabatic gas expulsion have a low SFE of 1/3,

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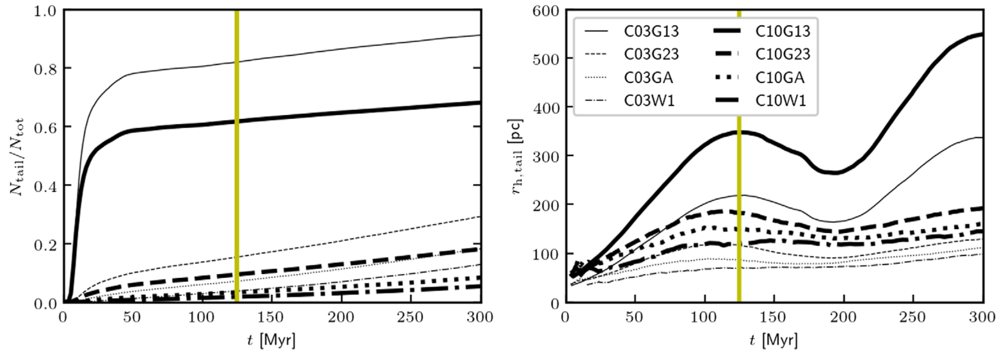

Figure 1. LEFT PANEL: The evolution of the fraction of the tail stars. RIGHT PANEL: The evolution of the radius, which encompasses 50 % of the tidal tail stars (an analog to the half-mass radius). The age of the Pleiades (at 125 Myr) is indicated by the vertical line.

they form substantially less populous tails because of their longer $\tau_{\rm M}$ (dotted lines). The gas free clusters (models C03W1 and C10W1; dash-dotted lines) form the least populous tails.

The radius, $r_{\rm h,tail}$, containing 50 % of the number of tail stars is shown in the right panel of Fig. 1. The models with rapid gas expulsion and a low SFE of 1/3 form the most extended tails; the extent of the tail then decreases with increasing SFE (models C03G23 and C10G23; dashed lines), and increasing $\tau_{\rm M}$ (models C03GA and C10GA; dotted lines). The gas free clusters form the least extended tails (dash-dotted lines). Note that the tails of clusters with rapid gas expulsion do not expand monotonically; they contract between 130 Myr and 190 Myr, whereupon they resume expansion. This happens because the stars released suddenly due to gas expulsion have different kinematics than the stars gradually escaping due to stellar dynamical processes. This is studied in Dinnbier & Kroupa (submitted).

The morphology of the tidal tails for the more massive clusters is shown in Fig. 2. The figure demonstrates some of the tail differences between models with different gas expulsion scenarios. Mainly, the populous large tail of model C10G13, which also tilts with time; and the shorter, slowly expanding, and S-shaped tails of the other models.

4. Predictions for the Pleiades

After interpolating in our models in mass to get the best match to the present day Pleiades for each considered scenario of gas expulsion, we obtain the following results:

• If the Pleiades formed with rapid gas expulsion and SFE = 1/3, they are surrounded by a populous tidal tail containing in total $40 - 170$ A stars, and having $r_{\rm h,tail} = 150 - 350$ pc.

• If they formed with rapid gas expulsion and SFE = 2/3, they are surrounded by a tidal tail containing in total $4 - 11$ A stars, and having $r_{\rm h,tail} = 100 - 200$ pc.

• If they formed with adiabatic gas expulsion and SFE = 1/3, they are surrounded by a tidal tail containing up to several A stars, and having $r_{\rm h,tail} = 40 - 100$ pc.

• If they formed with the SFE close to 100 %, their tidal tail has similar properties to the tail in the previous bullet point.

These estimates take into account the contamination due to field stars and interpolation in our models. The present day mass function between the cluster (assumed to be initially not mass segregated) and tidal tail differs only slightly in some of the models, which is not likely to be observed.

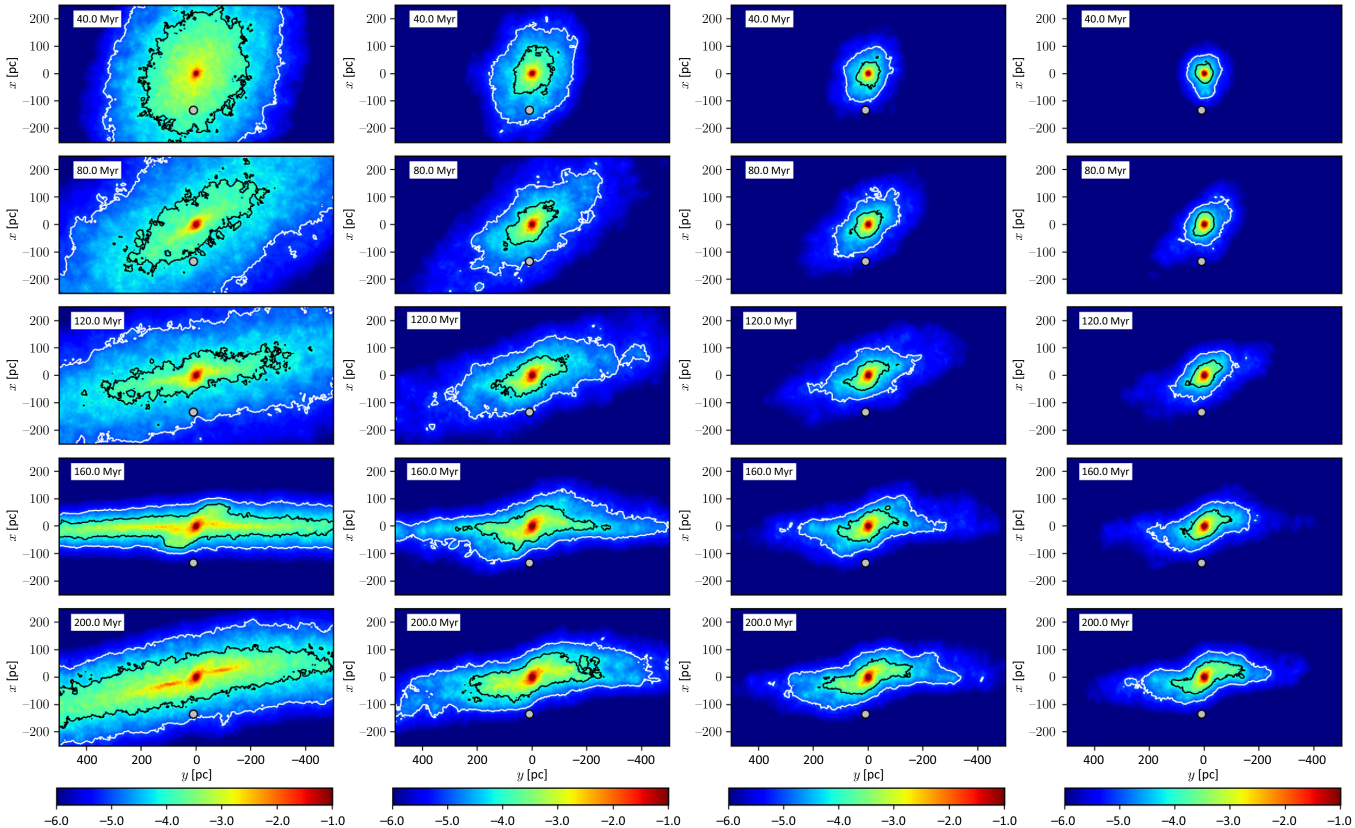

Figure 2. Number density evolution of the tidal tail in the Galactic midplane. From left to right, the columns show models C10G13, C10G23, C10GA and C10W1. The rows are time snapshots as indicated in their upper left corner. The axes x and y point to the Galactic anticentre, and in the direction of Galactic rotation, respectively. The position of the Sun relative to the Pleiades is shown by the circle at $(x, y) = (-130\,\mathrm{pc}, 30\,\mathrm{pc})$. The black and white contours enclose the number density of $1.0 \times 10^{-5}\,\mathrm{pc}^{-3}$ and $9.0 \times 10^{-5}\,\mathrm{pc}^{-3}$, respectively. This density corresponds to estimated contamination of field stars due to the Schwarzschild velocity distribution, and due to the Hyades-Pleiades stream, respectively.

The results imply that SFE $\lesssim 2/3$ with rapid gas expulsion leaves observational traces in the tidal tail; on the other hand, it would be hardly possible to find traces if the Pleiades formed with adiabatic gas expulsion. A future search of the tidal tail near the Pleiades (or other star clusters of a similar age), will also be important for constraining the conditions during gas expulsion from young star clusters.

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