An Expanding Trapezium Cluster?

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Summary

Simulations with Aarseth’s (1994) NBODY5 code are presented of an initially dense binary-rich cluster. It is assumed that the star formation efficiency is 50 per cent with instantaneous mass loss.

The model central density and velocity dispersion agree with the observational constraints if expansion is only about $6 \times 10^4$ yr old. Additionally, the observed binary proportion constrains the primordial proportion to have been significantly less than in Taurus–Auriga.

The claim that a variation of the birth binary proportion with gas cloud parameters has been detected, however, can only be verified if the cluster can be shown to be expanding rapidly.

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1. Introduction

The Trapezium Cluster in Orion is an important astrophysical laboratory for the study of the formation of stars and planetary systems, and of the early dynamical evolution of a young cluster rich in binary systems.

• It’s age is estimated to be younger than 5 Myr, and most probably only a few $10^5$ yr.

• The central stellar number density is unusually large for embedded clusters, with mean interstellar separations of about 6000 AU.

The distribution of orbital elements of a population of binary systems carries a memory of the dynamical history of this population. Short-period primordial binary systems are an energy reservoir, whereas long-period binary systems are an energy sink. The cluster and its constituent binary systems interact, which in part drives cluster evolution.

• Surveys of Galactic field main-sequence stars show that a significant fraction ($f_{tot} \approx 50\%$) are in binary systems (e.g. Duquennoy & Mayor 1991).

• Observations of sparse groups of pre-main sequence stars in Taurus-Auriga imply a significant overabundance ($f_{tot} \approx 1$) of binary systems (e.g. Köhler & Leinert 1998).

• In the Trapezium Cluster the binary proportion is comparable to the Galactic field value (Petr et al. 1998a,b, Prosser et al. 1994).

**QUESTION:** Can a Taurus–Auriga binary proportion have dynamically evolved to the reduced value, or is the Trapezium population primordial?
2. Models

2.1. The initial model Trapezium Cluster

- $N = 1600$ stars (point masses) (McCaughrean & Stauffer 1994).
- Half-mass radius $R_{0.5} = 0.1$ pc (McCaughrean & Stauffer 1994).
- IMF from Kroupa et al. (1993) for $m \leq 1 M_\odot$, and Scalo (1986) for $m > 1 M_\odot$.
- Lower and upper stellar mass limits of $m_l = 0.08 M_\odot$ and $m_u = 30 M_\odot$, respectively.
- Plummer density distribution.
- Initial position and velocity vectors are independent of stellar mass.
- Velocity distribution of the binary centre-of-masses is isotropic.

The resulting **cluster mass** is $M_{\text{cl}} = 700 M_\odot$. If the Trapezium Cluster were in virial equilibrium then the model **relaxation and crossing times** would be $t_{\text{relax}} = 0.62$ Myr and $t_{\text{cross}} = 0.1$ Myr, respectively.

The **virial ratio** $Q = E_{\text{kin}}/|E_{\text{pot}}| = 0.5$ in virial equilibrium. Here $Q = 1$.

The initial velocities are chosen to correspond to a system with a combined mass $M_{\text{stars}} + M_{\text{gas}} = 2 \times M_{\text{stars}}$. That is, it is assumed that the **massive stars** in the cluster have driven out a gas mass, $M_{\text{gas}} = M_{\text{stars}} = M_{\text{cl}} = 700 M_\odot$ (cf Churchwell 1997), immediately after they “turn on” and before any significant stellar-dynamical processes occur. This corresponds to a **star-formation efficiency** of 50 per cent.
2.2. Primordial binary systems

The total (summed over all periods) binary proportion is

$$f_{\text{tot}} = \frac{N_{\text{bin}}}{N_{\text{bin}} + N_{\text{sing}}},$$

(1)

where $N_{\text{bin}}$ and $N_{\text{sing}}$ are the numbers of bound binary and single star systems, respectively.

- $f_{\text{tot}} = 1$ assumes that the binary-star properties do not vary with star-forming conditions, apart from the effects of crowding, and that they are identical to what is observed in Taurus-Auriga.

- $f_{\text{tot}} = 0.6$ assumes that the binary-star properties vary with star-forming conditions in the sense suggested by Durisen & Sterzik (1994).

The initial model period distributions are compared with the observational data in Fig. 1.

Additionally, the following assumptions are made:

- The initial mass-ratio distribution is obtained by random pairing of the stars.

- The initial eccentricity distribution is thermally relaxed.

Fig. 2 shows the resulting initial eccentricity-period diagram, after pre-main sequence eigenevolution.
3. Results

- The central density and tangential velocity dispersion decrease rapidly due to the expansion. They are consistent with the observed values at time $t \approx 0.06$ Myr.

- Rapid expansion halts the disruption of binary systems at an early stage.

This is shown in Figs. 3 and 4.
Implications:

- The expanding model could be a reasonable description of reality if about 50 per cent of the mass of the cluster was expelled about 60 thousand years ago, at which time the present Trapezium Cluster would have gone into a rapid expansion phase. This solution implies an extreme youth of the gas-free Trapezium Cluster.

  This would be consistent with claims that the circum-stellar material seen around the young stars in the Trapezium Cluster should be removed within $10^4 - 10^5$ yr through photo-ionization by the most massive central star, $\theta^1$ C Ori (e.g. Bally et al. 1998).

- The model apparent binary proportion is consistent with the observational constraint for $t \gtrsim 0.05$ Myr, provided $f_{\text{tot}} \approx 0.6$ initially!

  This is lower than the binary proportion in Taurus–Auriga. If model B2 does represent reality, then this may be due to dynamical evolution in the proto-cluster prior to gas expulsion, or due to a dependency on cloud temperature as suggested by Durisen & Sterzik (1994).

Main shortcoming:

In the present study the Trapezium Cluster is treated as an isolated entity.

In reality, it appears to be the core of the much more massive and extended ONC, which is partially embedded in the parent elongated molecular gas cloud (Hillenbrand & Hartmann 1998).
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Table 1: **Initial conditions for the Trapezium Cluster models.** Three simulations are performed for each model. Column 5 contains the maximum binary-star period. The minimum period is $P_{\text{min}} = 1$ day in all cases. The form of the period distribution is defined in column 6, where K2 (Kroupa 1995a) refers to a birth distribution that is consistent with young systems in Taurus–Auriga, and DM91 (Duquennoy & Mayor 1991) refers to the Gaussian log-period distribution of the Galactic field. A 1 $M_{\odot}$ system has, with $\log_{10}P_{\text{max}} = 8.43$ (11) a semi-major axis of 8200 AU ($4.2 \times 10^5$ AU).
Fig. 1.— **Distribution of orbits, \( f_P \),** for main sequence multiple systems (solid dots, Duquennoy & Mayor 1991) and pre-main sequence systems in Taurus–Auriga (open squares; \( \log_{10} P > 4 \): Köhler & Leinert 1998, \( \log_{10} P = 3.5 \): Richichi et al. 1994, \( \log_{10} P < 2 \): Mathieu 1994). The dotted histogram is the initial period distribution from Kroupa (1995a). Crowding in the model Trapezium Cluster changes this distribution to the long-dashed one. A Gaussian log-period birth distribution that fits the solid dots, changes in the model Trapezium Cluster due to crowding to the distribution shown as the short-dashed line.
The initial eccentricity–period diagram for $f_{\text{tot}} = 1$. The distribution for $f_{\text{tot}} = 0.6$ is the same in eccentricity, but has fewer orbits for $\log_{10} P > 4$. The thick dashed line represents the observed envelope for main-sequence binary stars with a G-dwarf primary (Duquennoy & Mayor 1991).
Fig. 3.— **Upper panel:** The time evolution of the number of stellar systems within a spherical distance of $R = 0.053$ pc of the position of the density maximum of the model cluster. The thick curves assume no binary systems are resolved, and the thin curves count all stars. **Lower panel:** The time evolution of the velocity dispersion of centre-of-masses within a projected distance of $r = 0.41$ pc of the position of the density maximum of the model cluster. **In both panels,** the solid curves are for initially $f_{tot} = 1$ (model B1), and the dot-dashed curves are for initially $f_{tot} = 0.6$ (model B2), and the observational constraints with the Poisson error range are indicated by the dotted lines.
Fig. 4.— The time evolution of the apparent binary proportion in the model Trapezium Clusters. The solid line is for initially $f_{\text{tot}} = 1$ (model B1) and the dot-dashed line is for initially $f_{\text{tot}} = 0.6$ (model B2). **Upper panel:** observational constraints from Prosser et al. (1994, $r = 0.249$ pc, $d_1 = 26$ AU, $d_2 = 440$ AU) are shown as dotted lines. **Lower panel:** observational constraints from Petr et al. (1998a, $r = 0.04$ pc, $d_1 = 63$ AU, $d_2 = 225$ AU) are shown as the horizontal lines. Here, the central dotted line is $f_{\text{app}}$ for all systems in their sample, and the central dashed line is $f_{\text{app}}$ for the low-mass systems only. Poisson uncertainties are indicated by the upper and lower horizontal lines.