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DYNAMICAL MODELS OF STELLAR ASSOCIATIONS

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Numerical N-body investigations of the dynamical evolution of a young stellar aggregate embedded in a massive interstellar cloud are presented. We discuss some mechanisms of the formation of OB-associations – traditional as well as new ones.

KEY WORDS Stellar dynamics, star clusters, stellar associations

1 INTRODUCTION

OB associations are unbound, expanding stellar systems. They contain hundreds to thousands of massive stars. There are considerably more low mass stars than OB stars in associations and consequently almost all stars that form in the Galaxy probably form in OB associations. But the origin of associations remains a mystery: there is, as yet, no successful theory of association formation.

On the other hand, most extremely young stars are embedded in giant molecular clouds (GMCs). There stars apparently form in rich star clusters from massive cores of dense molecular gas. However, most of these clusters must be disrupted soon after they emegre from GMC, otherwise there would be more open clusters in the Galactic field than are observed (Lada and Lada, 1991). The explanation of the transition from these temporal star clusters to unbound stellar association is a very interesting task for stellar dynamics. Here, we discuss some mechanisms of the formation of stellar associations and present some new results obtained with our numerical model. We investigate a numerical N-body model of a stellar aggregate embedded in a gas cloud which is disrupted by the energy outflow of massive stars. The main goal of the investigation is to try to understand how the unprocessed gas influences the dynamics of a young stellar aggregate.

2 HISTORY

In the beginning of the 1950s, a popular hypothesis of star formation was the idea of dust aggregation under stellar radiation pressure, and consequent gas accretion on these dust cores. Fred Hoyle developed a scenario of "periodical rejuvenation" of massive stars during their accidental penetration through the interstellar clouds. Moving from the cloud, these bright and massive stars look like an OB-association! Unfortunately, this elegant hypothesis is only historically interesting now.

Öpik (1953) created a very fruitful idea of star formation in cooling gas around supernova remnants. He suggested that expanding shells from a supernova explosion could sweep up and compress interstellar material from which new stars are formed. These newly formed stars would retain the outward motion of the supernova shell and form an unbound association which was expanding away from the original site of the supernova explosion.

Oort (1954) proposed a similar scenario for association formation based upon the expansion of the H II region neutral cloud material. According to his scenario, clumpy structure of the cloud led to the formation of inbound stellar association around a progenitor O star.

Within a few decades, this Öpik–Oort idea of stimulated star formation was applied to H I supershells, which are formed under the collective action of many young massive stars. According to this paradigm, any example of young star concentrations near the shell was interpreted as evidence of stimulated star formation.

Completely different idea for association formation was created simultaneously with the Öpik–Oort scenario. According to Zwicky (1953) and McCrea (1955), the formation of massive stars in a temporal cluster leads to the heating and escaping of unprocessed gas from this cluster. This increases the cluster energy and forces their expansion. If the energy reaches a positive value, the cluster loses its gravitational bound state and forms an expanding association. This simple idea did not attract much attention and was "rediscovered" a quarter of a century later, just after the first observations of dense protostellar groups situated inside the nuclei of molecular clouds.

The dynamics of OB associations and, more importantly, their genesis have not so far been studied well enough. It is possible to combine both of these attractive Zwicky–McCrea and Öpik–Oort ideas for the numerical model of a young stellar aggregate. That is why we also include in our model stimulated star formation. We will try to distinguish between first and second (i.e. stimulated) population stars of the OB association being modelled.

The low value of star formation efficiency (SFE) in GMCs is of central importance for understanding the dynamical nature of OB associations (see the analytic approximations of, for example, Hills, 1980). The unbound state and expansion of the associations is a natural consequence of star formation with a low conversion efficiency of gas to stars followed by rapid removal of the unprocessed gas from the system. The stars, which were originally bustling in virial equilibrium with the deep potential well of the GMC's core, respond to the rapid removal of the majority of the binding mass by freely expanding into space with their initial virial velocities. That is why the expansion velocities of stellar associations are close to the velocity dispersion of the GMC's gas, i.e. ≈ 5 km s^{-1} (Blaauw, 1991).

There were a few numerical simulations of the early stages of dynamical evolution of temporal star clusters as the residual star-forming gas is removed from the system (see Wilking and Lada, 1985). The results of these N-body calculations can be summarized as follows. The stability criterion for the formation of a bound cluster in the solar vicinity requires the final stellar density of the cluster to exceed $0.1 M_\odot$ pc^{-3}, i.e., that density which is stable against shear from galactic tides. For a rapid gas release time ($\tau_R \leq 10^6$ yr), a value of SFE $\geq 50\%$ is necessary to form a bound cluster. For $\tau_R > (4\text{–}5) \times 10^6$ yr (corresponding to 4 to 5 crossing times) the numerical models are reduced to analytic models for adiabatic gas release and a SFE of only 20–30% is required to result in tidally stable bound stellar systems.

Simple evaluation (Surdin, 1989, 1994) gives a theoretical prediction for the value of the large-scale SFE as a function of the initial GMC mass ($M_{\rm cl}$):

$$\mathrm{SFE} \approx 0.4\% \left(\frac{M_{\rm cl}}{10^6 M_\odot}\right)^{1/2} \tag{1}$$

For the mass range of GMCs ($10^5 M_\odot$ to $4 \times 10^6 M_\odot$) we obtain a predicted value of SFE $\approx$ 0.1–1%. Indeed, observations indicate that the overall efficiency of star formation in GMCs is small; only about 0.1–5% of the total gaseous mass is ever converted to stars in such clouds (Duerr *et al.*, 1982; Carlberg, 1985). Consequently, the inevitable destruction of a GMC by H II regions, stellar winds, and supernovae which accompany the formation of new stars, results in the dispersal of the majority of the initial binding of the star-forming complex. Therefore, an unbound system of stars is left behind, expanding into the field with a velocity on the order of a few km s^{-1}, characteristic of the velocity dispersion in the original molecular cloud core.

Still missing from all these investigations, however, is the next step: that of modelling the gravitational interaction of stars with gas after the disruption of the temporal cluster. Furthermore, it is interesting to find the concentration of stars near a massive gaseous shell, which is theoretically predictable. This goal is one of the prime motivations for our numerical investigation.

3 MODEL

We carried out a numerical simulation of the dynamical evolution of a young stellar aggregate embedded in a massive interstellar cloud. We used the N-body Aarseth code with initial $N \sim 10^3$. The initial mass distribution of our "stars" was a Salpeter distribution. This stellar aggregate is embedded in a spherical "cloud" with initial density distribution $\rho \propto R^{-2}$ for $R \leq R_0$ and $\rho = 0$ for $R > R_0$. The gas was represented in the numerical code by an additional term in the gravitational

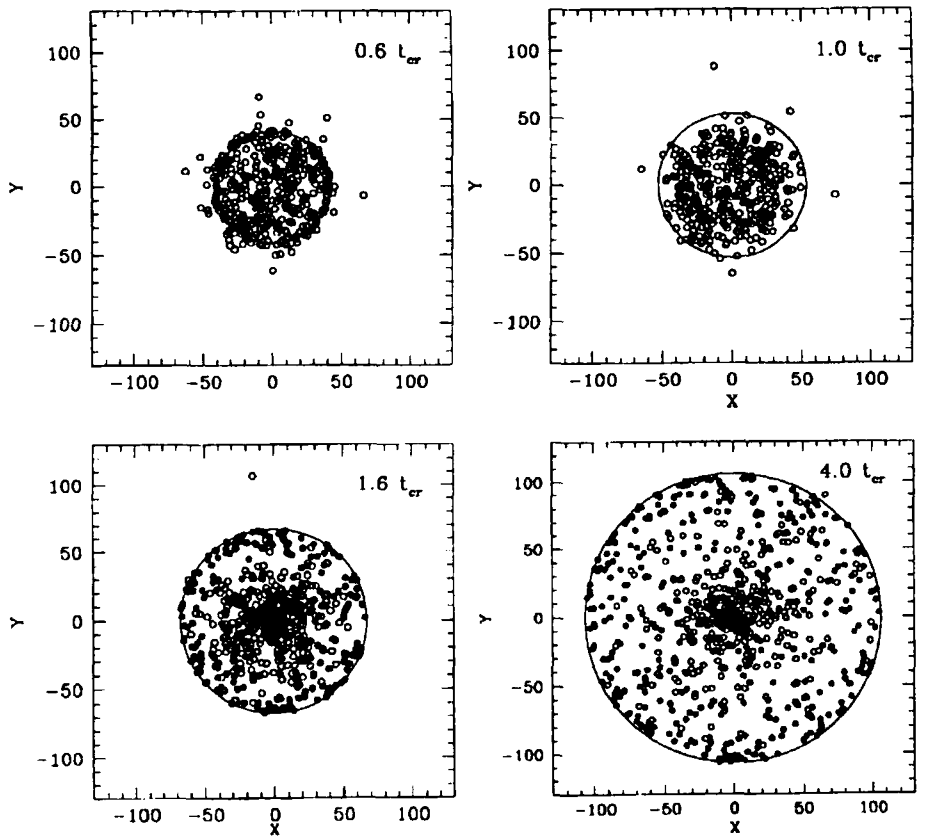

Figure 1 Evolution of the young stellar aggregate embedded in a massive cloud. The model is represented in a sky projection. The shell radius is marked by a big circle. The time is indicated in the upper right corner of each frame. *Open circles*, stars of initial generation; *filled circles*, stars of second generation whose formation was stimulated by the shell.

potential function determining the stellar motion. The value of the SFE (just before gas dispersal) was a free parameter.

Initially a good relaxed velocity distribution of "stars" was assumed. We included rotation of the stellar component in some models. For these models the chaotic component of the star velocity was about 0.3–0.4 of the velocity of rotation of the stellar system. The initial radius of the stellar component of the aggregate was about 2.0 in arbitrary units. The initial half-mass radius of the stellar component was about 0.65 for models with strong rotation and about 0.4 for models without rotation.

After a few dynamical timescales, the cloud begins to be disrupted by the energy of massive stars. The gas of the cloud forms an expanding spherically symmetric envelope of radius $R_S(t)$. All the gas inside this radius is swept up to form a very thin envelope. We used a few different analytic approximations for the shell radius:

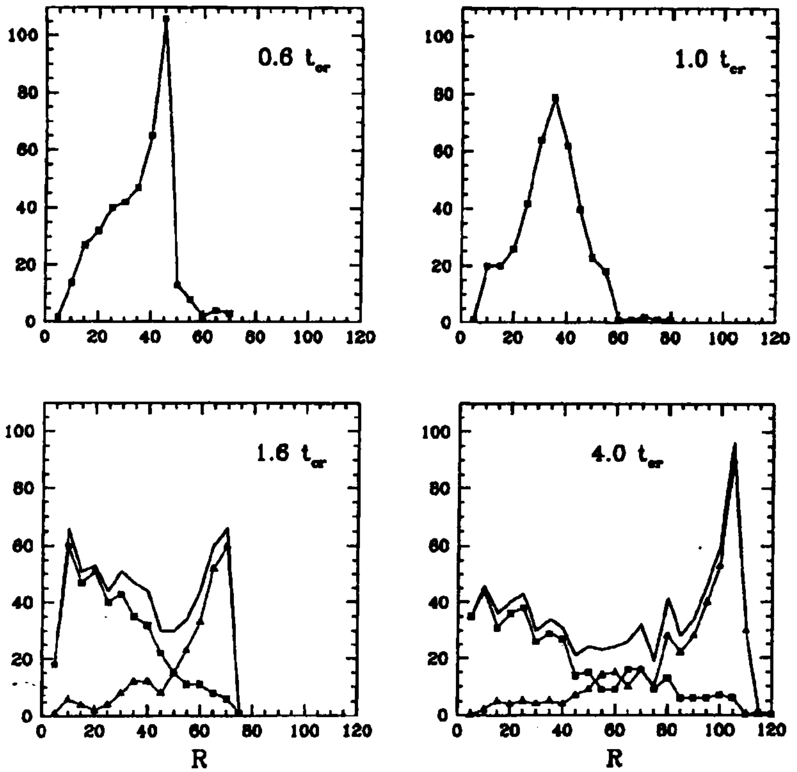

Figure 2 The radial distribution of stars for the model represented in Figure 1. *Squares*, the initial population of stars; *triangles*, stars of second generation; *solid line*, total population.

from $R_S(t) \propto t$ to $R_S(t) \propto t^{1/2}$ according to the results of numerical simulations (Silich, 1992).

The main parameters of our models are dimensionless. The time intervals are expressed in units of initial central dynamical time $t_{\rm dyn} \approx (G\rho_0)^{-1/2}$. The initial cloud radius is $R_g \approx$ 10–50. The total mass of the first generation ("old") stars is $M_1 = 1$, and the total mass of the second generation ("new") stars is $M_2 = 4$. All the new stars have the same individual mass $m_2 = 0.01$, but the old stars have a Salpeter mass function: $dN/dm_1 \propto m_1^{-2.35}$ with a ratio of $m_{\rm max}/m_{\rm min} = 20$.

All the new stars are formed randomly during the period of time between $t_{\rm cr}$ and $t_{\rm fin}$, localized in the random points of the expanding envelope, and with space velocities equal to the current envelope velocity. The total calculation time is $t = 4t_{\rm cr} = 2t_{\rm fin} \sim 10^2 t_{\rm dyn}$.

As an example, in the model shown in Figures 1 and 2, the initial cloud radius is $R_g = 50$ and the mass is $M_g = 1000$, the star formation termination time is $t_{\rm fin} = 70$, the number of old stars is $N_1 = 400$, and the final number of new stars is the same: $N_2 = 400$.

4 RESULTS

The gravitational interaction of a star association with the circumstellar gas gives some interesting effects, one of which is *dynamical cooling* of stars. This effect leads to the long-term movement of the stars close to the boundary of the envelope. This can mimic stimulated star formation in the shell.

For all our models with $R_S(t) \propto t$ the main stage of interaction between the stars and the shell takes place during only a few initial crossing times of the stellar component, so we conclude that the exact value of the expansion velocity of the shell is important only in the very early stage, when the radius of the shell is comparable with the initial size of the parental cloud (or its subcondensation).

Some stars may cross the system a few times, decreasing their energy each time. Finally, from 20% to 50% of stars may form a gravitationally bound cluster under the action of dynamical cooling. In spite of the fact that the star formation efficiency may be as low as 10%, this cluster can survive.

Taking into account the effect of stimulated formation of second-generation stars in the expanding envelope we compare the relative spatial and velocity distributions of both star populations. In the general case, we are able to distinguish between these two populations only by the radial velocity distribution.

5 CONCLUSION

Up to now, we do not know whether associations emanate from dense temporal clusters (i.e. from compact GMC nuclei) or from entire GMC. The first case means they begin an expansion from a small volume almost axially symmetrically, thus we may apply our model of young stellar aggregate (YSA) evolution to the observations.

The main conclusions from our model are the following:

(1) The YSA can produce a gravitationally bound cluster if the expansion velocity of the shell is slow enough even when the local value of the SFE is as low as 10%. This occurs as a result of the dynamical cooling effect which forces some of the newborn stars to form an open cluster.

(2) For systems with significant rotation and low SFE the dichotomy between the formation of bound clusters and unbound associations is very sharp. It is difficult to find initial conditions that lead to the formation of a bound cluster together with an unbound association of approximately equal masses.

(3) Multiple supernova outbursts play an important role for cloud disruption and OB-association expansion. But in the later stages of the process, the massive shell can play the most important dynamical role for the evolution of the stellar aggregate. The combination of parental cloud rotation and the massive shell slowing down force a significant number of stars to concentrate near the shell. This mechanism is a plausible candidate to create an effect which can mimic induced star formation.

(4) The expanding star association can accompany the gaseous envelope for a long time due to the gravitational slowing down of the stars by the massive supershell. Structures like this are observed in some well-known objects, for example, around NGC 2070 in the LMC (Seleznev, 1995).

(5) Some models with rotation lead to the formation of significantly flattened clusters. This flattening is due to the anisotropy of the velocity distribution and does not correspond to the angular momentum of the cluster.

(6) During the evolution of a YSA, a significant number of its stars is able to form a few gravitationally unbound subgroups with mass from 1% to 10% of the total YSA mass. These subgroups look like separate associations or temporal clusters.

(7) The formation of wide stable binaries is quite possible. We have found a few massive binary systems formed from an initially uniform stellar aggregate.

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