# THE DYNAMICAL EVOLUTION OF YOUNG OPEN CLUSTERS

Michael Margulis and Charles J. Lada
University of Arizona, Steward Observatory
Tucson, Arizona 85721 U.S.A.
David Dearborn
Lawrence Livermore National Laboratory
P. O. Box 808, Livermore, California 94550 U.S.A.

Using numerical N-body calculations we have simulated the dynamical evolution of young clusters as they emerge from molecular clouds. Starting with initially virialized systems of stars and gas we follow the evolution of these systems from the time immediately after the stars have formed in a cloud until a time long after all the residual star-forming gas has been dispersed. In the models stellar systems were composed of 50, and in some cases 100, stars and these stars were represented as point masses. The stellar mass function followed a power law with an index of -2.5 and ranged over two decades in mass (Scalo 1978). Gas in the models was represented as an extra term in the gravitational potential function governing stellar motions, and was set to follow a density distribution corresponding to a spherically symmetric Plummer potential function (Plummer 1911). Starting with these initial conditions, stellar motions were then integrated and evolution of each stellar system was followed as gas was dispersed from the vicinity of the stars as a function of time.

From these simulations we have found that whether a cloud produces a cluster depends primarily on two parameters: the star formation efficiency (i.e. fraction of total system mass which is stellar) at the time of gas removal and the duration of that gas removal from the system (Hills 1980, Mathieu 1983, Elmegreen 1983, Wilking and Lada 1983). Clusters which remain bound after gas removal undergo significant expansion and may lose a large fraction of their stars. Figure 1 below displays the fraction of stars which remain in a bound system after gas removal versus the initial star formation efficiency. Triangles and circles represent actual models run. For models 1, 2, and 3, gas removal was instantaneous, while for models 4 to 7 gas was removed over three initial system cross times, and for models 8 and 9 gas was removed over four initial system crossing times.

Comparison of the initial and final states of our models with observations of molecular clouds and young open clusters allowed us to place constraints on the initial mass densities, radii, and velocity



*J. Goodman and P. Hut (eds.), Dynamics of Star Clusters, 463–465.*


https://doi.org/10.1017/S0074180900147680 Published online by Cambridge University Press

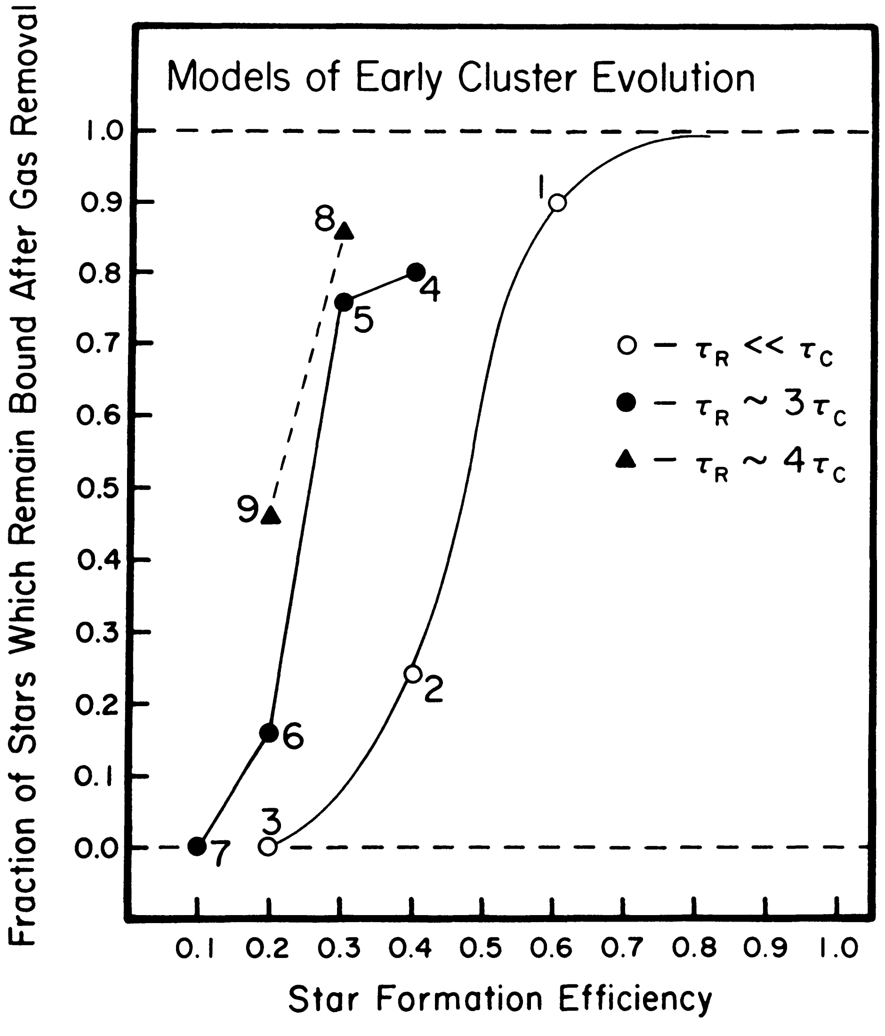


**Figure 1.** The fraction of stars which remain bound after gas removal as a function of star formation efficiency. The different symbols correspond to different gas removal times.

dispersions of clouds likely to produce open clusters. In particular, we find that in order to produce final clusters similar to the Pleiades, protocluster star formation must occur in the relatively dense (hydrogen number density > $10^3$ - $10^5$ $cm^{-3}$), small (size ~ 0.1 - 1.0 pc) condensations found in molecular clouds. In addition, star formation efficiencies in excess of 30% and gas removal times of at least one million years are required in order for these clumps to evolve into such clusters. In fact, even more stringent requirements on cluster forming regions may exist since the tidal shear due to the parent molecular clouds on emerging protoclusters may be significant.

https://doi.org/10.1017/S0074180900147680 Published online by Cambridge University Press

In light of a global star formation efficiency in our galaxy of only 0.1% - 5.0% (Blaauw 1964, Duerr, Imhoff, and Lada 1982), it is not yet clear whether these very high efficiencies, which are required to form clusters, can be achieved in typical molecular clouds. There is, however, one cloud where such high efficiencies have been observed. This is the Ophiuchus cloud, with a star formation efficiency of at least 25% (Lada and Wilking 1984) and relatively quiescent gas dynamics. In this cloud, stellar winds from recently formed stars might be capable of slowly dispersing the gas on time scales of three million years or more (Lada, Margulis, and Dearborn 1984).

Although it may be difficult to achieve high efficiencies in clouds intrinsically, initial conditions in the dynamical structure of clouds may help to enhance the star formation efficiencies there. If the size scale of turbulence in clouds is much less than the Jean length, or if non-gravitational forces are important in the dynamical equilibrium of the gas, stars may form with little or no kinetic energy with respect to the center of mass of the cloud. In this case a newly formed protocluster of stars will quickly collapse and reach a virialized state in about a free fall time, well before significant gas dispersal is likely to occur. Although the subsequent dynamical evolution of the system will then proceed in a way similar to that in the models described above, the star formation efficiency at the time of gas removal will be significantly enhanced over the initial value. For example, calculations concerning such a collapse in constant density clouds indiate that the star formation efficiency in such clouds could be enhanced from 20% to 46% (Lada *et al*. 1984). Since the star formation efficiency is a pivotal parameter governing the likelihood that a particular cloud will produce a cluster, knowledge of these dynamical factors may ultimately be very important in the study of cluster formation.

## REFERENCES

Blaauw, A. 1964, *Ann. Rev. Astr. Ap.*, **2**, 213.
Duerr, R., Imhoff, C. L., and Lada, C. J. 1982, *Ap. J.*, **261**, 135.
Elmegreen, B. G. 1983, *M.N.R.A.S.*, **203**, 1011.
Hills, J. G. 1980, *Ap. J.*, **235**, 986.
Lada, C. J., Margulis, M., and Dearborn, D. 1984, *Ap. J.*, **285**, in press.
Lada, C. J., and Wilking, B. A. 1984, *Ap. J.*, in press.
Mathieu, R. D. 1983, *Ap. J. (Letters)*, **267**, 97.
Plummer, H. C. 1911, *M.N.R.A.S.*, **71**, 460.
Scalo, J. M. 1978, in *Protostars and Planets*, ed. T. Gehrels (Tucson: University of Arizona Press), p. 265.
Wilking, B. A., and Lada, C. J. 1983, *Ap. J.*, **274**, 698.