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THE EVOLUTION OF EMBEDDED SMALL CLUSTERS

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A young open cluster is a *2-phase system*:

- an ensemble of **stars** move in a **gaseous** medium (the mother molecular cloud).

The *dynamics* and *thermodynamics* of the system, and so its
–*evolution* and *final fate* (is it stable or unstable?)

strongly depends on the mutual feedback between gas and stars.

We present an approach which consists in a (simplified) model where stars (N–bodies) move within a gaseous spherical molecular cloud. The two components influence each other through

– *gravity* and *mass loss*.

Among other results (role of IMF, SFE, stellar background, etc., see **Conclusions**), we find that a significant fraction of small clusters can be destroyed even

– **before** SN explosion.

when a *significant* amount of massive stars are present.

THE MODEL

After the Lada, Margulis and Dearborn (1984, ApJ 285, 141 LMD) work not much has been done to study *quantitatively* the early evolution and fate of stellar clusters embedded in their mother cloud, following numerically the N–body dynamics of stars moving in a (dispersing) gaseous cloud. The LMD model was not fully self–

consistent, for the gas was assumed to expand with an assumed time law; by the way, this work gave relevant information on the capability of a stellar system to **remain bound after gas removal** in dependence on the star formation efficiency (SFE).

– An answer to the crucial question:

- *what conditions on IMF and on SFE allow a small cluster, emerging from a molecular cloud, to remain bound?*

– **necessarily** implies that the mutual feedback between gas and stars is **taken into account**.

To get really *reliable* results one should couple an **N-body code** to a **fully hydro-code** to model the radiative and mechanical interaction between the *stellar* and *gaseous* phases. This has been partially done (see Capuzzo–Dolcetta and Di Lisio, *SPH in Astrophysics*, 1994, Mem.S.A.It., 65, 1107), and is the target of future work (Capuzzo–Dolcetta, Di Lisio, Navarrini, Palla, in preparation).

Results good to order of magnitude, can however be obtained with the present model, which treats the coupled dynamics and thermodynamics of stars and gas in a cluster with the following:

approximations

- the gas cloud evolves in time keeping *spherical shape* and a spatially *uniform* density.
- the gravitational force exerted by stars on the cloud is approximated.

The Equations

The relevant equations are:

$$\left\{ \begin{array}{l} \vec{a}_i = \frac{\vec{F}}{m_i} - \frac{dm_i}{dt} \frac{\vec{v}_i}{m_i} \quad i = 1, \dots, N \\ \ddot{R} = \ddot{R}_g + \ddot{R}_p + \ddot{R}_* + \ddot{R}_{ml} + \ddot{R}_{vr} \\ \dot{U} = \dot{U}_p + \dot{U}_{vr} + \dot{U}_{ml} + \dot{U}_{SN} \end{array} \right.$$

which is a $6N + 3$ order system submitted to the appropriate initial conditions.

- \vec{a}_i is the *i-th* star's acceleration,
- R is the gas–sphere radius,
- U is the gas internal energy.

In the gas *motion* equation:

$$\ddot{R}_g = -\frac{GM}{R^2} \quad (\text{self - gravity})$$

$$\ddot{R}_p = \frac{3\gamma(\gamma - 1)U_g}{M_g R_g} \quad (\text{pressure field})$$

$$\ddot{R}_* = \frac{1}{M} \sum_{i=1}^N f_i \quad (\text{stellar - gravity})$$

$$\ddot{R}_{ml} = \sum_{i=1}^N \left(1 - 2\frac{r_i^3}{R^3}\right) \ddot{R}_{ml_i} \quad (\text{stellar mass - loss})$$

$$\ddot{R}_{ml_i} = \frac{1}{M} \dot{m}_i v_{ml_i}$$

$$\ddot{R}_{vr} = -\frac{k_{vr}}{M + M_*} \left(M\dot{R} + \sum_{i=1}^N m_i \dot{r}_i \right) \quad (\text{viol. relax.})$$

- f_i is an approximation of the force exerted by the i -th star on the gas cloud.
- v_{ml_i} is the i -th star wind speed (taken from the literature).

In the gas *energy* equation:

$$\dot{U}_p = \frac{9}{5} \gamma(\gamma - 1) \frac{\dot{R}U}{R} \quad (\text{pressure heating})$$

$$\dot{U}_{vr} = \frac{3}{5} k_{vr} \frac{M}{M + M_*} \dot{R} \left(M\dot{R} + \sum_{i=1}^N m_i \dot{r}_i \right) \quad (\text{viol. relax.})$$

$$\dot{U}_{ml} = \frac{3}{5} M \dot{R}_g \sum_{i=1}^N \left| \left(1 - 2\frac{r_i^3}{R^3}\right) \ddot{R}_{ml_i} \right| \quad (\text{star mass - loss})$$

$$\dot{U}_{SN} = \delta(t - t_{SN}) e_{SN} \quad (\text{SN contribution})$$

Parameters of the models

Stars are initially *uniformly* distributed in space and velocity in a sphere of radius R_{*0} with velocities to satisfy the given virial ratio (here assumed =1).

The relevant initial parameters are:

Stars:

$$N = \text{number of stars}$$

$$R_{*0} = \text{initial cluster radius} = 1 \text{ pc}$$

$$IMF \propto m^{-\alpha}, \quad 0.2 \leq m/M_{\odot} \leq 20$$

$$\text{local SFE} \equiv \varepsilon$$

$$\text{chemical composition} = (X, Y, Z) = (0.7, 0.27, 0.025)$$

$$\text{virial ratio} \equiv \nu_0 = \frac{2 \times \text{kinetic energies}}{\text{potential energy}} = 1$$

Gas Clump:

$$R_0 = \text{initial radius} = R_{*0}$$

$$\rho_0 = \text{initial gas density} = 500 M_{\odot}/\text{pc}^3$$

$$\dot{R}_0 = \text{initial collapse velocity} = 0$$

$$U_0 = \text{initial internal energy}$$

CONCLUSIONS

- A small cluster ($N \lesssim 100$, $0.2 \leq m/M_{\odot} \leq 20$) embedded in a gas clump of typical density $\rho \simeq 500M_{\odot}/pc^3$

is **lost** to the background

at the time $t \simeq 10Myr$ when first SN explode (see *Fig. 1*), if $SFE \lesssim 0.4$.

- When $SFE > 0.4$, the cluster **resists** to the explosion whenever the IMF is **not biased** towards **large masses**.

- When the exponent of the IMF $\propto m^{-\alpha}$ is **sufficiently negative** ($\alpha \lesssim -2$) and $SFE \gtrsim 0.35$, the gas cloud and its embedded cluster are **disrupted by powerful stellar winds** in a shorter time (few *Myrs*). In this case,

↓

just **very high** SFE allow the cluster to survive (*Fig. 2*, *Fig. 3* and *Fig. 4*).

- The capability to distinguish a small cluster over a background **strongly depends** on the *cut-off* magnitude (the density contrast falls of a factor 50 when V_{cut} is changed from 14 to 18 !). This means that *intrinsically bound* cluster can be **misconsidered as unbound** just because they are observed over a too crowded background:

↓

so any practical definition of cluster lifetime **must** take into account the background over which the cluster is projected (*Fig. 5* and *Fig. 6*).

Figure Captions

Fig. 1 : Super-Nova explosion time vs star mass (chemical composition $X = 0.7$, $Y = 0.27$, $Z = 0.025$).

Fig. 2 : Gas cloud dissolution time vs SFE for the IMF exponent $\alpha = -2$.

Fig. 3 : Rough delimitation of regions of bound and unbound clusters in the (α, ε) plane, where $\alpha = \text{IMF exponent}$, $\varepsilon = \text{SFE}$.

Values of ε above the upper horizontal line have not yet been investigated.

Fig. 4 : For the models whose α , ε , N are labelled on the top :

solid lines — cluster Lagrangian radii of 25%, 50%, 75% and 100% of the mass

dashed lines - - gas cloud radii.

Bottom panels are the enlargements of the upper ones.

Fig. 5 a,b : Time evolution of the cluster density contrast $\Delta\rho/\rho_{bg} = (\rho - \rho_{bg})/\rho_{bg}$. V_{cut} is the lower luminosity cut-off of the background, which is taken at latitudes $b = 0^\circ$ and $b = 45^\circ$ (upper and lower curves, respectively, in each panel). Horizontal lines correspond to $\Delta\rho/\rho_{bg} = 1$, below which the cluster is undistinguishable over the estimated background. The various cases studied label the panels.

Fig. 6 : Enlarged view of part of Fig. 5b, to show clearly the transition from "visible" to "invisible" cluster.

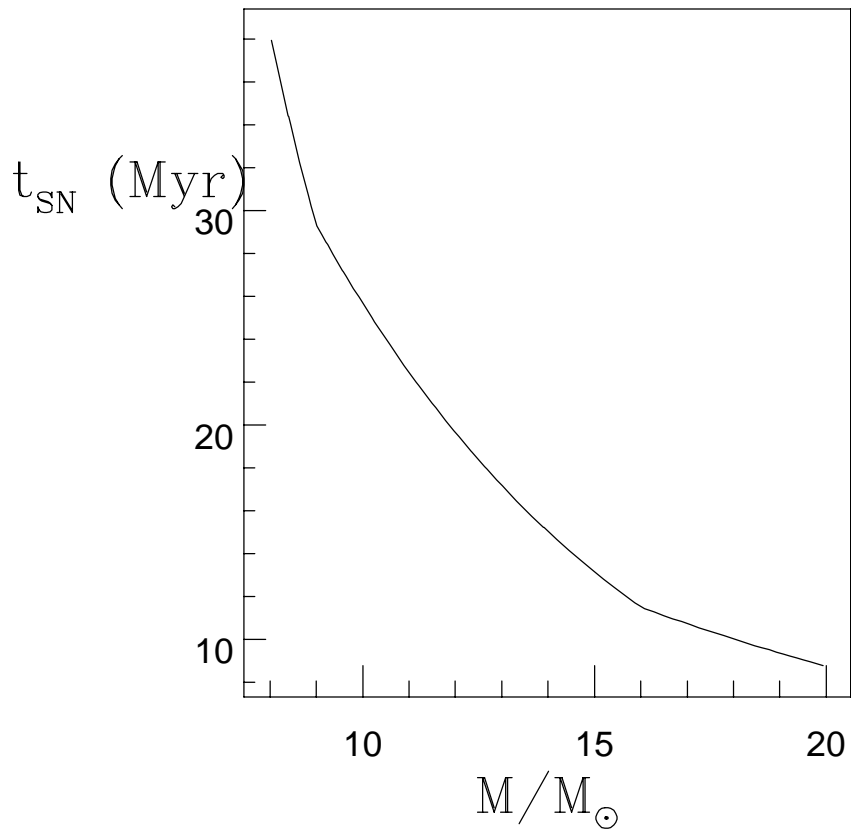


Fig. 1

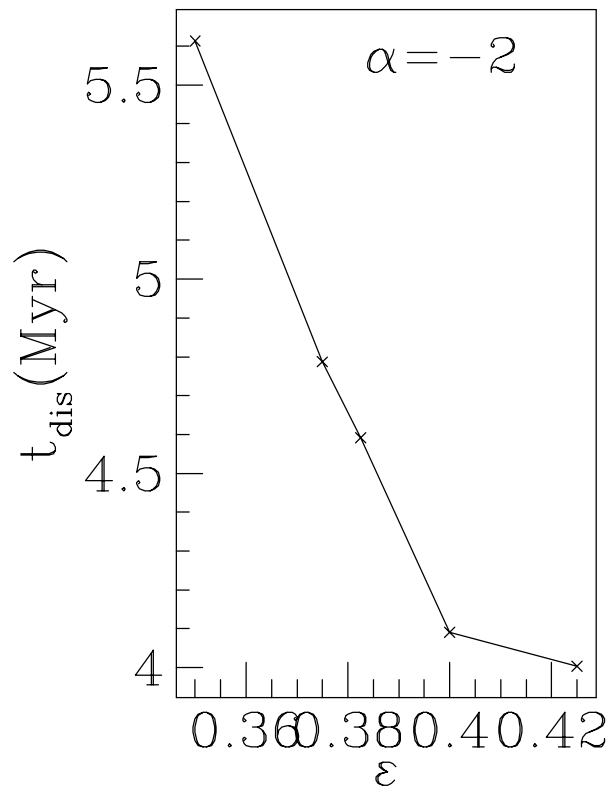
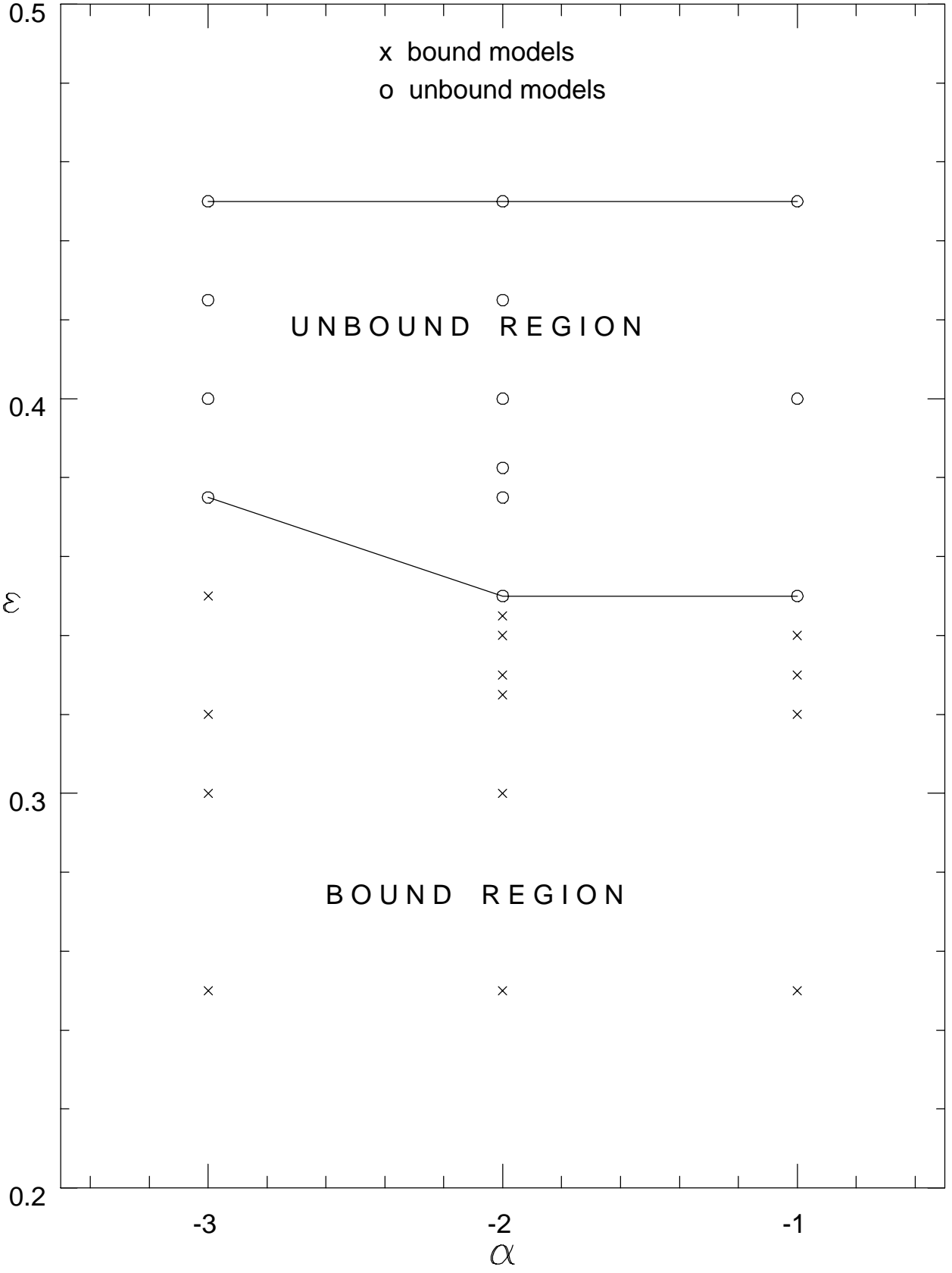
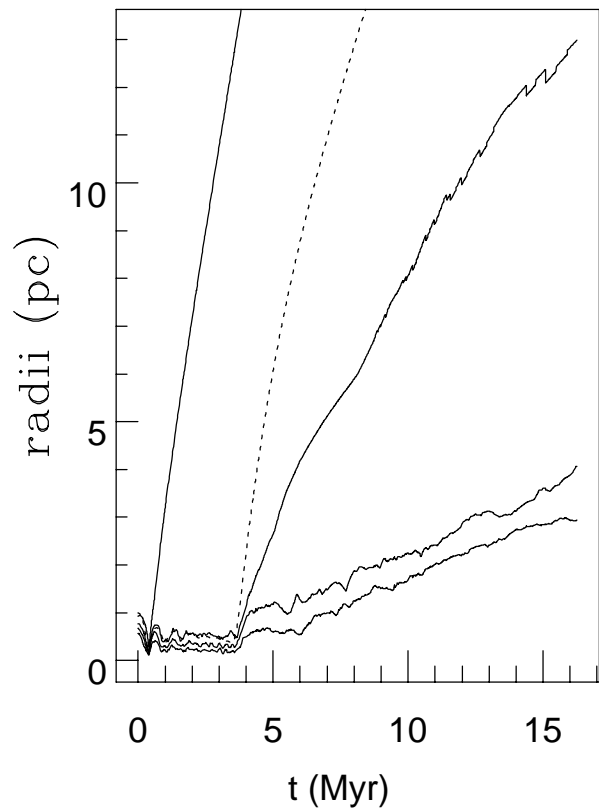


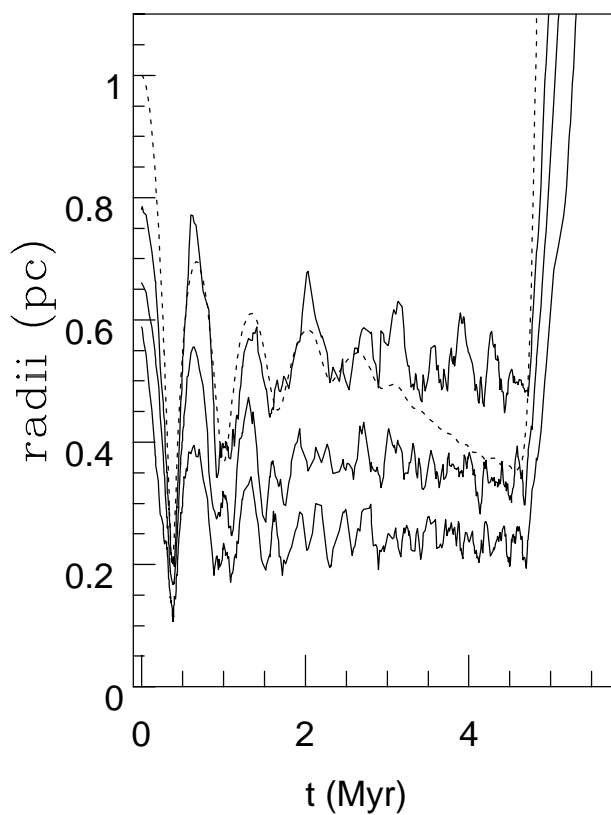
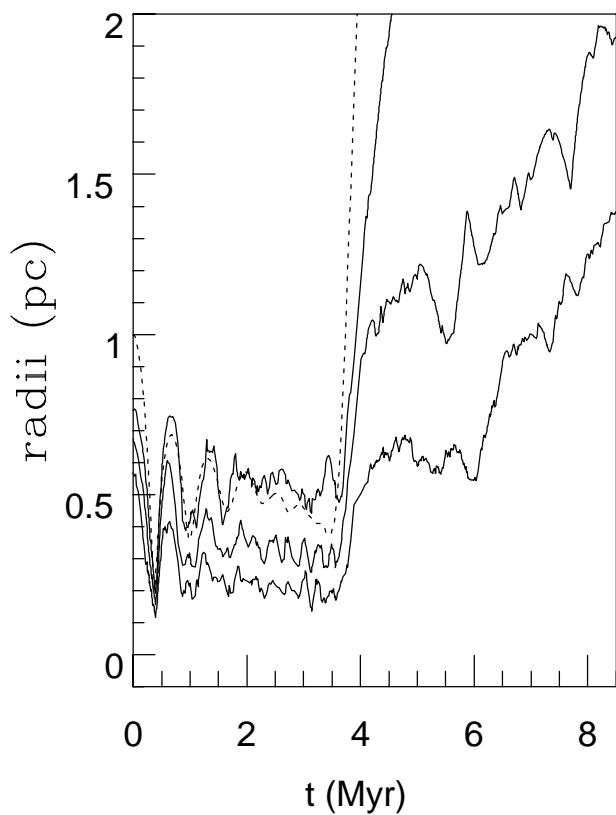
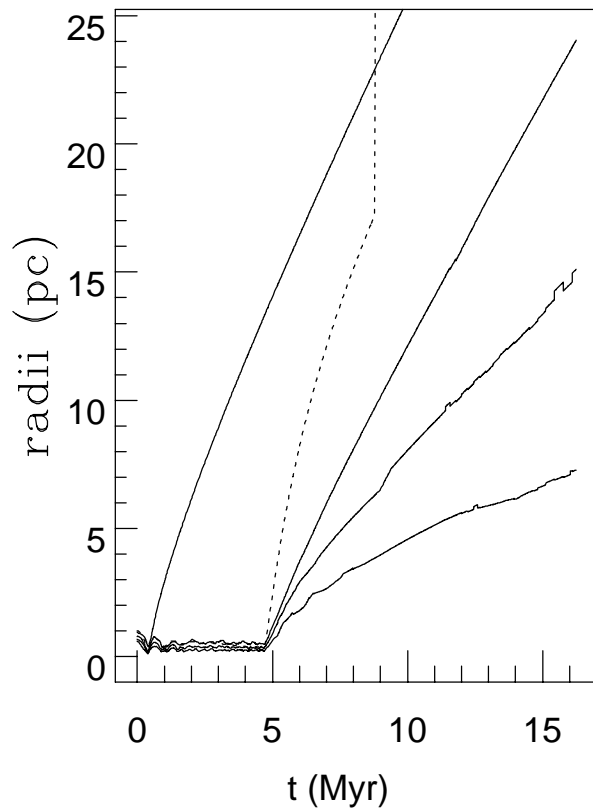
Fig. 2



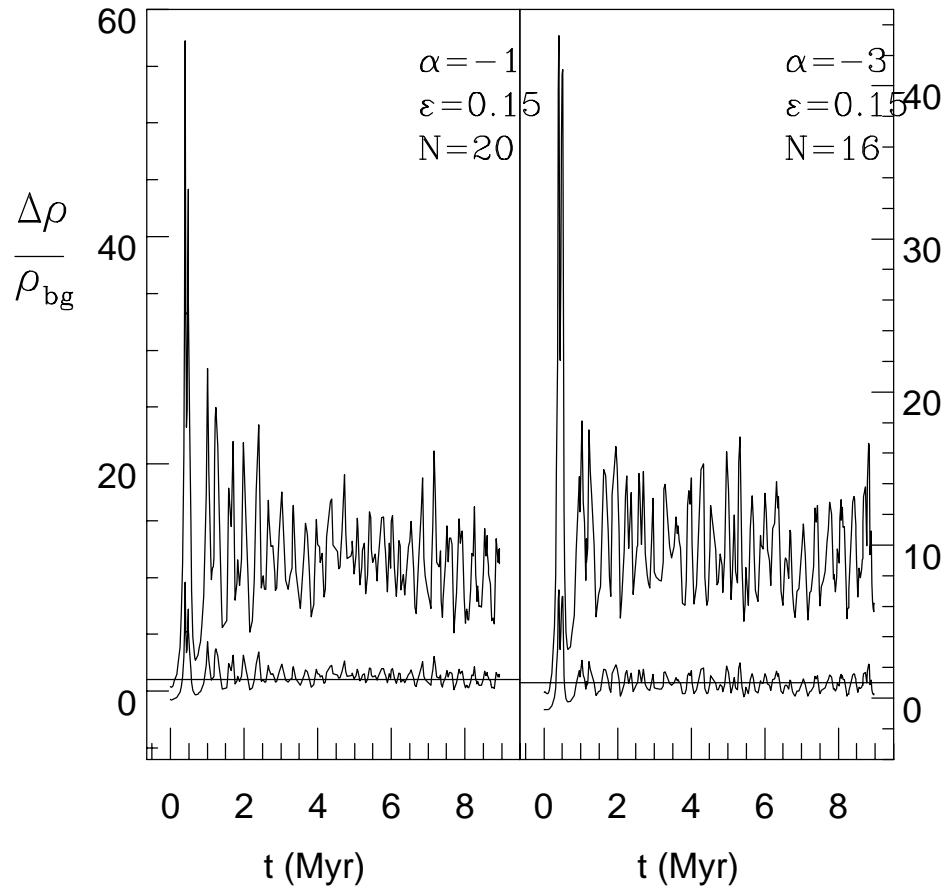
$\alpha = -3$ $\varepsilon = 0.45$ $N = 78$



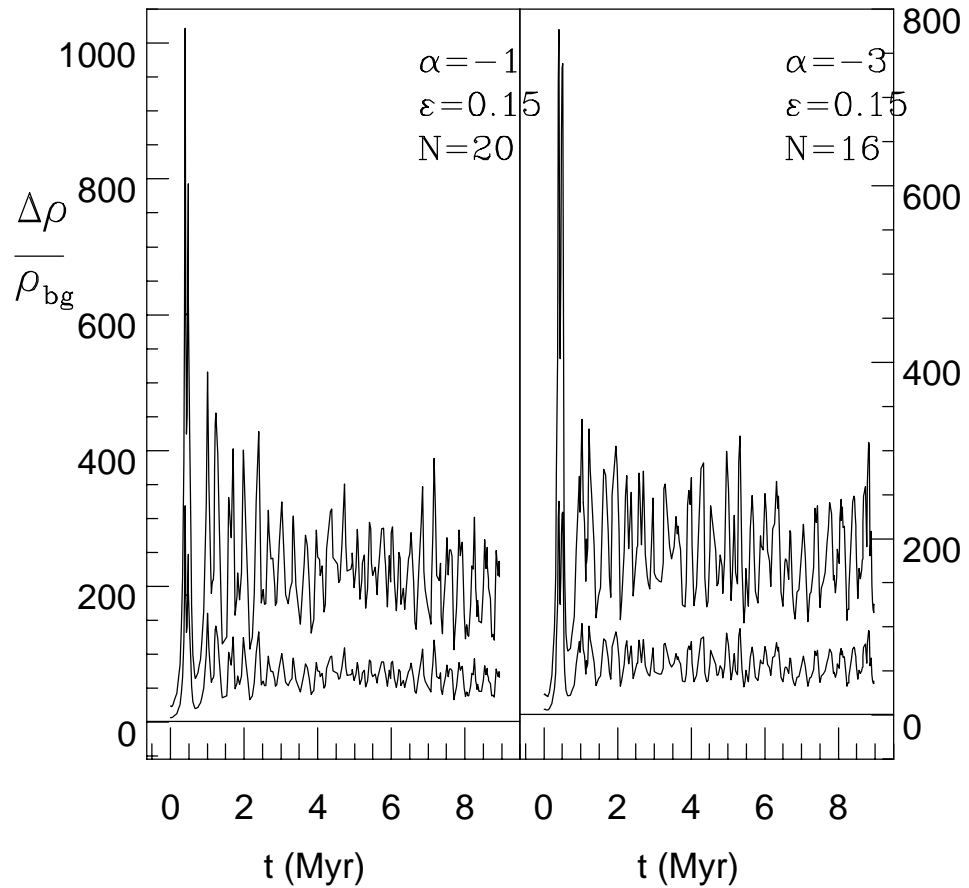
$\alpha = -1$ $\varepsilon = 0.45$ $N = 93$



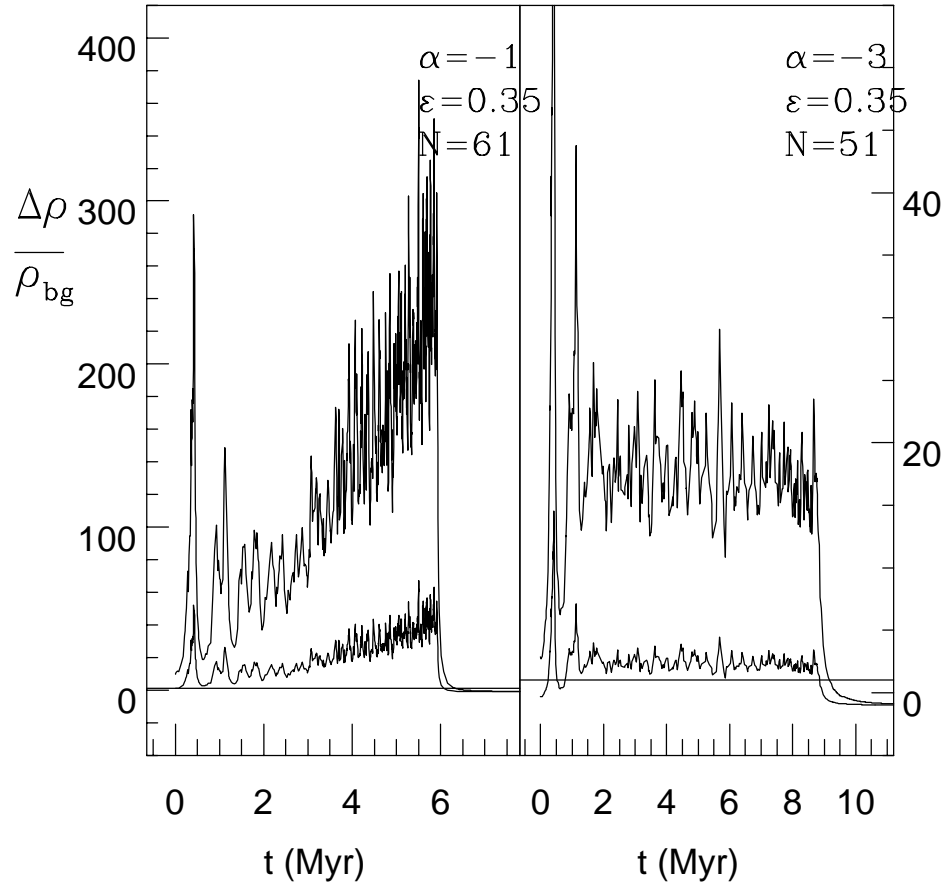
$$V_{\text{cut}} = 18$$



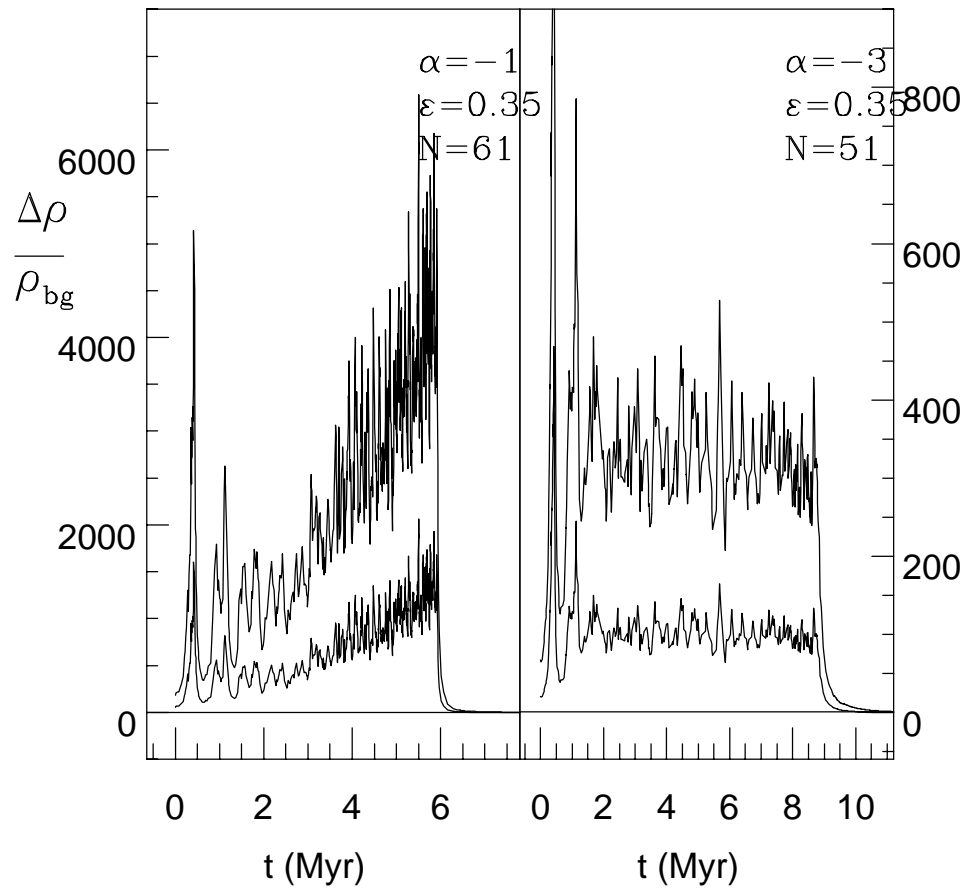
$$V_{\text{cut}} = 14$$



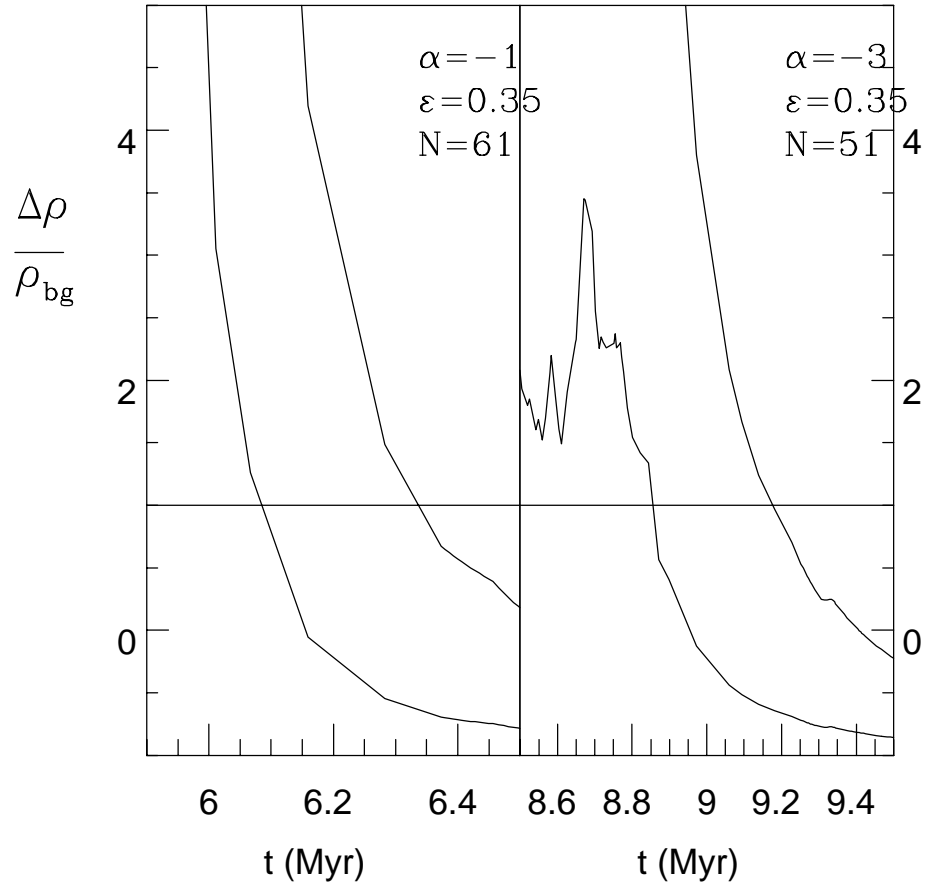
$$V_{\text{cut}} = 18$$



$$V_{\text{cut}} = 14$$



$$V_{\text{cut}} = 18$$



$$V_{\text{cut}} = 14$$

