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VIOLENT RELAXATION IN ISOLATED STAR CLUSTERS

Abstract. We study the effect of initial mass function and stellar evolution on the survivability of isolated star clusters after instantaneous gas expulsion. Our model clusters form with a centrally peaked star-formation efficiency profile according to the local-density-driven cluster formation model. We perform direct $N-$body simulations of $N_* = 10^4$ star clusters with global star-formation efficiencies ranging from 0.13 to 0.50.

We have found that the stellar evolutionary mass-loss does not affect the number of bound stars of star clusters with high global SFE ($SFE_{gl} > 0.2$), and the decrease in final bound mass fraction is only due to stellar evolution. But star clusters with lower global SFE are affected more by stellar evolutionary mass-loss and survive with less number of stars than if it would consist of single-mass non-evolving stars. High-SFE clusters also do not expand much after violent relaxation, while clusters with $SFE_{gl} = 0.15$ and 0.20 expand significantly. The global SFE as low as $SFE_{gl} = 0.30$ is sufficient for a cluster to almost keep its mass and size at the time of gas expulsion in our models.

Keywords. galaxies: star clusters: general – methods: numerical – stars: kinematics and dynamics – open clusters and associations: general.

1 Introduction

Stars do not form in isolation. Instead they form in large groups and clusters within dense clumps in giant molecular clouds. Different stellar-feedback mechanisms as stellar winds, radiation pressure and photo-ionizing radiation coming from massive stars ($> 8M_{SUN}$) can drive the star-forming gas with the speed about $10km/s$ (i.e. roughly$10pc/Myr$) [1, 2, 3, 4, 5]. Star-formation efficiency (SFE), the fraction of star-forming gas mass converted into stars, reported by observations of nearby star- forming regions to be usually less than 30% [6, 7, 8]. That means, more than 70% of total mass is driven from the embedded clusters by the gas expulsion, which leads to the instability in the star cluster. Lada and Lada [9] reported that about 90% of star clusters in the solar neighborhood are disrupted after gas expulsion. There are many works dedicated to the topic of survivability of young star clusters after gas expulsion in the literature [eg. 10, 11, 12, 13, 14, 15, 16, 17, among many others].

Shukirgaliyev et al. [16] proposed a new approach to study the survivability of star clusters after instantaneous gas expulsion. They consider star clusters formed according to the local-density-driven cluster formation model of Parmentier and Pfalzner [18]. That is in their model clusters the volume density profile of stars are steeper than that of the residual and total gas, as a consequence of star-formation taking place with a constant efficiency per free-fall time in a centrally concentrated, spherically symmetric clump gas [18]. They reported that, such star clusters with a centrally peaked SFE profile are more resilient to the instantaneous gas expulsion than the model clusters considered earlier [e.g. 13, and references therein]. The model star clusters of Shukirgaliyev et al. [16] survive the instantaneous gas expulsion with a critical global SFE of $SFE_{gl} = 0.13$ instead of $SFE_{gl} = 0.33$ as estimated previously.

In this study we consider the survivability of isolated cluster models only in contrast to Shukirgaliyev et al. [16], who mainly focused on the survivability of star cluster in the tidal field of our Galaxy, orbiting in the solar neighborhood. The isolated cluster models in Shukirgaliyev et al. [16] have been considered mainly to test their new initial conditions and simulations. Their isolated model clusters are consist of equal-mass, non-evolving stars, while their model clusters of the solar neighbourhood consist of evolving stars with masses sampled according to the initial mass function (IMF) of Kroupa [19]. Therefore, the decrease of the cluster bound fractions at the end of violent relaxation caused by coupled effect of two mass-loss mechanisms: stellar evolution and tidal stripping [16, 20, 21, 22]. The intermediate case of isolated model clusters consist of evolving stars is now being considered in the framework of this study in addition to Shukirgaliyev et al. [16].

We compare the survivability of isolated model clusters of Shukirgaliyev et al. [16], which consist of equal-mass stars with our new simulations with full stellar mass spectrum where additionally stellar evolution taken into account. The gas expulsion is assumed to be instantaneous in both cases.

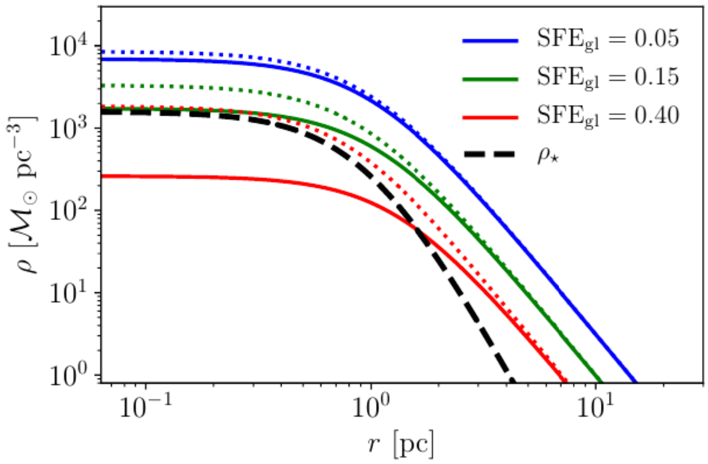

Figure 1 - Density profiles of the star cluster (black dashed line), of the residual (solid lines), and initial (dotted lines) gas for different SFE_{gl} in scaled physical units. A total stellar mass $M_* = 6000 M_{SUN}$ and a 3D half-mass radius $r_h = 1.26 pc$ are assumed. Note that the stellar density profile is a Plummer profile.

2 Model description

Our model clusters have a Plummer density profile and are in virial equilibrium together with the gravitational potential of the residual star-forming gas, immediately before gas expulsion. The density profile of residual gas is recovered for a given global SFE using the Eq. A.7 of Shukirgaliyev et al. [16], assuming that our model clusters have been formed with a constant star-formation efficiency of $\in_{ff} = 0.05$ from centrally concentrated, spherically symmetric gas clump. As a consequence of that, the volume density profiles of the residual and the total gas have a shallower slope that that of stars [18, 16]. Figure 1 shows the volume density profile of stars (black dashed line), of the residual (colored solid lines) and of the initial total gas (colored dash-dotted lines) of $M_* = 6000 M_{SUN}$ cluster with a global SFE of 0.05,0.15 and 0.40 for illustration.

Isolated model clusters of Shukirgaliyev et al. [16] have number of star $N_* = 10000$ in their simulations. In this study, we run a new set of simulations of isolated clusters in order to qualify the effect of stellar mass function and stellar evolutionary mass loss on the cluster survivability. For that we chose $M_* = 6000 M_{SUN}$ model clusters, which have $N_* = 10455$ stars when we sample stellar masses with IMF of Kroupa [19]. Upper and lower limits of $m_{up} = 100 M_{SUN}$ and $m_{low} = 0.08 M_{SUN}$ have been adopted for the IMF. We use the same normalization of our N-body units to physical as in Shukirgaliyev et al. [16] standard case. That is our $M_* = 6000 M_{SUN}$ model clusters have a half-mass radius of $r_h = 1.26 pc$ at the time of gas expulsion.

We generate the initial phase-space distribution of star in our model clusters using the program mkhalo from falcON package [23] with specially developed Gas Potential plug-in [16, 21]. The high-presicion direct N -body code phiGRAPE-GPU [24] has been used for our N -body simulations, which ended at time about $t = 1 Gyr$.

3 Bound fraction of isolated models

The bound fraction is the fraction of cluster mass immediately after gas expulsion, remaining bound to the cluster at a given time. The bound fraction could be also considered as a number fraction of bound stars. In case of clusters consist of non- evolving (i.e. constant mass) equal-mass stars, the bound fractions in terms of mass and number of stars are the same. But when we consider clusters consist of evolving stars, stellar masses decrease with time and two bound fractions become different. Therefore in this study in contrast to Shukirgaliyev et al. [16] we consider both, bound mass fraction and bound number fraction of our isolated model clusters.

We use the same method as we used in Shukirgaliyev et al. [16] to define the bound fraction of model clusters. That is, instead of defining the bound fraction based on the total (i.e., kinetic + potential) energy of stars as the fraction of stars with a negative

total energy (solid lines in Fig. 2), we eliminate unbound stars by iterative calculations of the total energies of stars after removing of currently unbound ones. This method, described in the appendix of Shukirgaliyev et al. [16] gives us the opportunity to to define the final bound fraction early on in the evolution of clusters. Otherwise, the bound fraction of model clusters, which are super-virial after gas expulsion, can be overestimated by the early method based on the total energies of stars [see the appendix of 16, for more details]. Figure 2, brought here from Shukirgaliyev et al. [16] for the sake of clarity, shows the comparison of the two methods of defining of the bound fraction of isolated model clusters. Dashed lines show the bound fraction calculated by a new technique, while the solid lines correspond to the bound fractions calculated by the old technique. Figure 2 shows that the instantaneous bound fraction converges toward the final bound fraction determined with our technique by the end of the simulations. This shows that with our calculation method we can estimate the final bound fraction even before the inner part of the cluster starts to collapse back and return to virial equilibrium. We caution, however, that with this method we underestimate the final bound fraction of a cluster with a low global SFE during their early evolution after instantaneous gas expulsion. This is caused by removing all un- bound stars, including the centrally concentrated ones, which contribute the most to the gravitational field of the cluster [see Fig. B.2. in 16]. This is the reason for the unusual behavior of the final bound fractions of isolated clusters with a global SFE of 0.13 and 0.15, which is 0 at $t \leq 1\ Myr$, and why they rise at an early time in the evolution instead of decreasing.

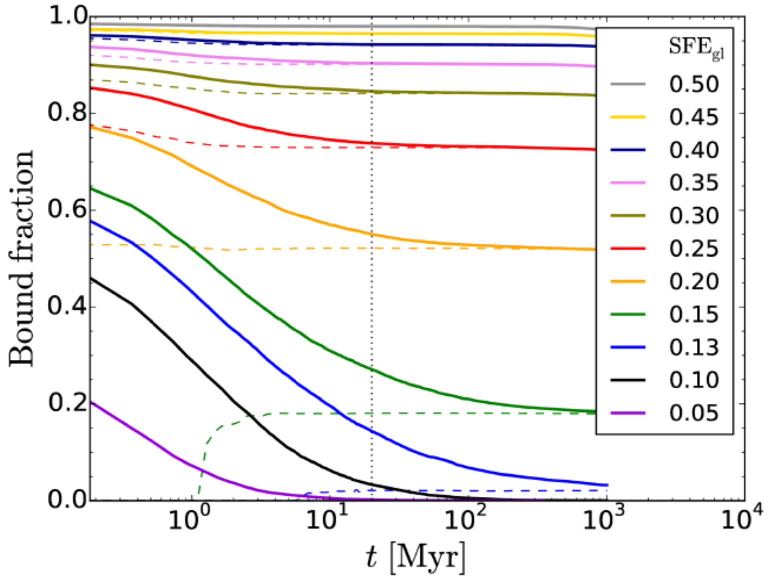

Figure 2 - Time evolution of the bound fraction F_b of isolated models ($N = 10^4$) as defined by two methods: defined by the fraction of stars with a negative total energy (solid lines), and defined by recalculating the total energy of stars in an iterative process (see text for details; dashed lines). The vertical dotted line corresponds to $t = 20\ Myr$ when we scale the isolated models with the same scale factor as for a non-isolated model with $M_* = 6000 M_{SUN}$, which also has $N \approx 10^4$.

(This figure brought here from Shukirgaliyev et al. [16] for the sake of clarity.)

4 Results

We use the technique described above to find the bound fractions of our newly simulated star clusters. Since we are looking at the multi-mass stars and turn on the stellar evolution, we consider two bound fractions, one in terms of number fraction, and the other in terms of mass fraction. In Fig. 3 we compare bound fraction evolution of two isolated models. The left panels show the bound fraction evolution of previous model clusters consist of equal-mass stars. The right panels show the bound number fraction evolution on top panel and bound mass fraction evolution in bottom panel of our newly simulated clusters, consist of IMF sampled evolving stars. The $SFE_{gl} = 13$ model cluster does not survive the instantaneous gas expulsion when is consist of multi-mass evolving stars (see blue lines in the right panels).

Figure 3 shows that after $t = 20\ Myr$ the bound number fraction of all model clusters become almost a constant, so the decreasing of the bound mass fraction of star clusters with IMF is only due to stellar evolution. Therefore we assume that the violent relaxation is over before $t = 20\ Myr$ and then we measure the final bound fraction, that is the bound fraction at the end of violent relaxation at $t = 20\ Myr$.

Figure 4 presents the comparison of the final bound fractions of our model clusters as a function of global SFE, in terms of number fraction in the left and of mass fraction in the right panel. Single mass model clusters and evolving clusters with IMF are represented by green and red colours, respectively. There is almost no difference between the two types of models when we look at the final bound number fraction for a high global SFE ($SFE_{gl} > 0.2$). The decrease in final bound mass fractions of star clusters with IMF mostly caused only by the stellar evolutionary mass-loss and also by Poisson noise in the phase space distribution of stars. The model cluster with the highest SFEs ($SFE_{gl} = 0.5$) save almost all of its stars after instantaneous gas expulsion (see bound number fraction). Therefore its bound mass fraction at the end of violent relaxation is almost the same as if it did not lose any star during its evolution with mass-loss caused by only the stellar evolution (the horizontal dashed line on the right panel of Fig. 4). It also do not too much differ in its bound mass at the end violent relaxation from other two high SFE clusters (

$SFE_{gl} = 0.3$ and $SFE_{gl} = 0.4$). These three model clusters do not expand much after the violent relaxation too (see Fig. 5). The half-mass radius of model clusters at the end of violent relaxation normalized to their half-mass radii immediately after gas expulsion[1] as a function of the global SFE are provided in Fig. 5. As we see from our models, the highest observed SFE, as high as $SFE_{gl} = 0.3$, is sufficient to keep the embedded clusters almost unchanged in terms of mass and size after gas expulsion. [See e.g. 25, to learn about the expansion of star clusters after gas expulsion].

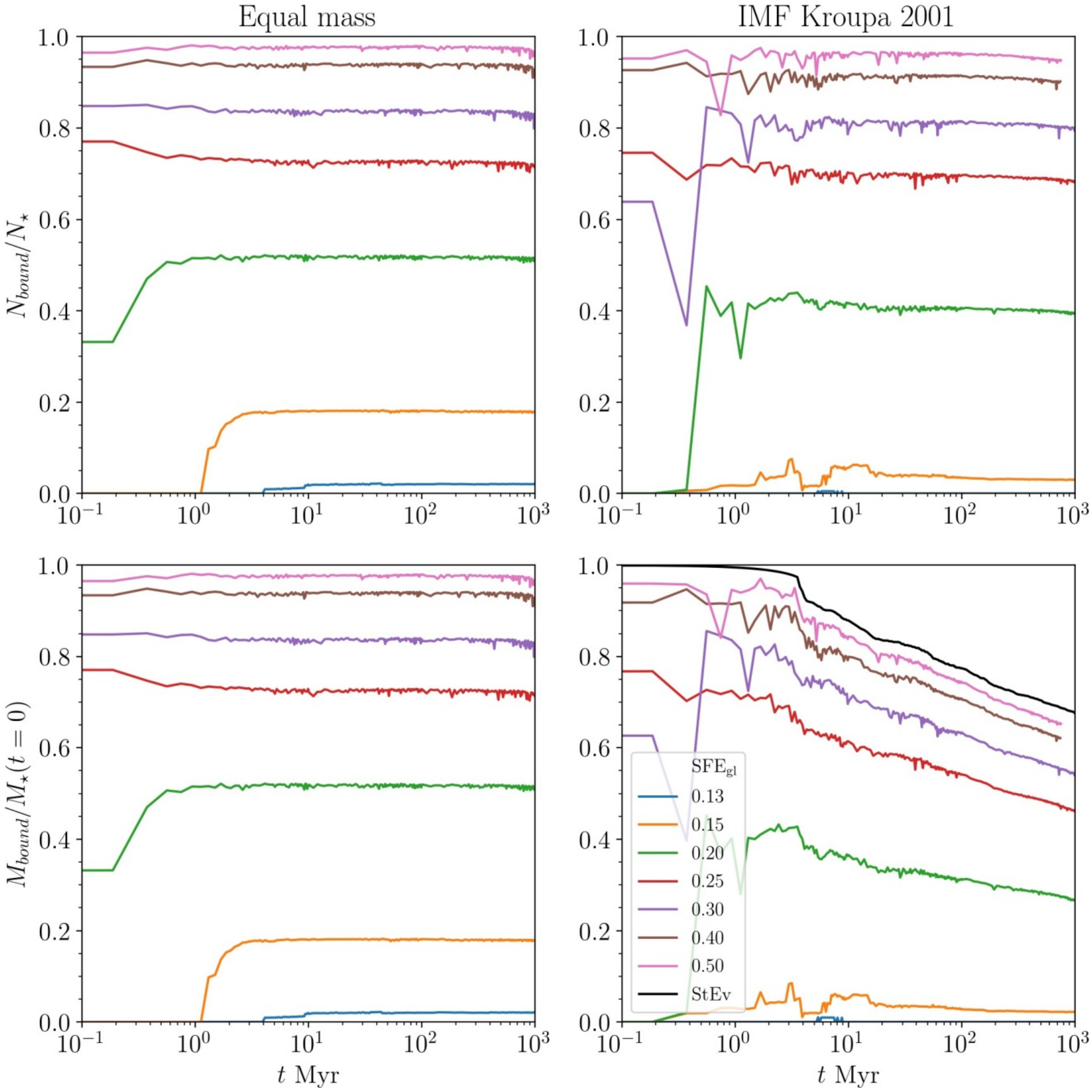

Figure 3 - Bound fraction evolution of isolated clusters. The top panels show the evolution of bound number fraction, while the bottom panels show the evolution of bound mass fraction of equal-mass star clusters in the left panels and IMF sampled evolving star clusters in the right panels. X-axis is given in logarithmic scale. The color-coding corresponds to global SFE shown in the key in the lower right panel. The black line in the lower right panel corresponds to the mass-loss due to pure stellar evolution

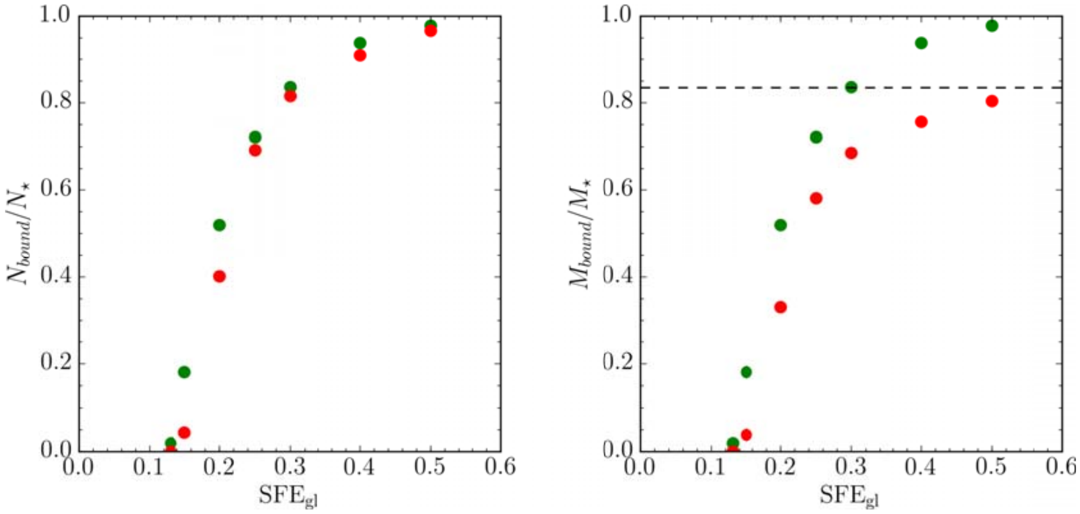

Figure 4 - The final bound fractions of isolated model clusters measured at $t = 20\ Myr$ as a function of global SFE. The left panel shows final bound fractions in terms of number fraction of stars, while the right panel corresponds to the final bound mass fractions. The equal-mass star clusters are marked with green colour, while model clusters with stellar evolution are shown by red

When we look at star clusters with global SFE lower than $SFE_{gl} < 0.25$, their final bound number fractions are decreased together with their final bound mass fractions when the IMF and the stellar evolution are introduced in the simulations. This is an effect of the fast evolution of most massive stars, when almost 15% of the total stellar mass is lost within early 20 $Myrs$. Due to the stellar evolutionary mass-loss, the central gravitational well of multi-mass clusters becomes much weaker, than that of single-mass clusters, and therefore loses more stars (hence mass). The escape of some very massive stars also have negative influence in the survivability of multi-mass low SFE clusters. The Poisson noise in the initial phase-space distribution of stars also can cause a scatter in the final bound fractions of low-SFE clusters [see 20, for more details].

[1] Since clusters have the same stellar density profile at the time of instantaneous gas expulsion, their half-mass radii immediately after gas expulsion are identical too.

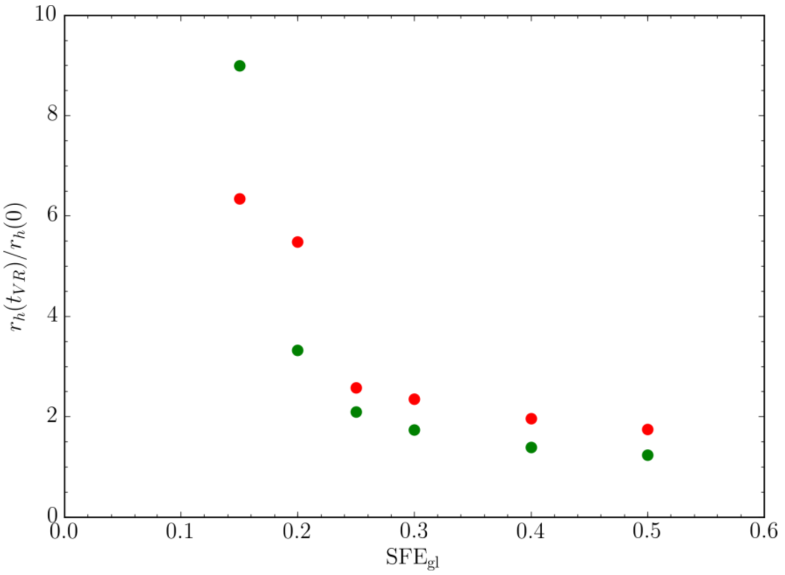

Figure 5 - The half-mass radii of isolated model clusters at the end of violent relaxation as a function of global SFE, normalized to the cluster half-mass radii immediately after gas expulsion ($r_h(0) = 1.26\,pc$). The green and the red filled circles correspond to the single-mass and multi-mass clusters, respectively.

5 Conclusions

We considered the survivability of isolated model clusters, consist of multi-mass evolving stars after instantaneous gas expulsion. Our model clusters formed with a centrally-peaked SFE profile, as a consequence of star formation process happening with a constant efficiency per free-fall time according to the model of Parmentier and Pfalzner [18]. All our model clusters have a Plummer density profile immedi- ately before gas expulsion and are in virial equilibrium with gravitational potential of the residual gas. We consider $M_* = 6000M_{SUN}$ clusters with different global SFE range from $SFE_{gl} = 0.13$ to $SFE_{gl} = 0.5$. The IMF of Kroupa [19] with the mass limits of $m_{low} = 0.08M_{SUN}$ and $m_{up} = 100M_{Sun}$ has been adopted. All stars lose their mass according to the stellar evolution code SSE [26]. We use high-precision direct N-body code phiGRAPE-GPU for our simulations.

We calculated the bound fraction of model clusters based on their energies using the technique described in Sec. 3. Then we compare our results with the results in Shukirgaliyev et al. [16] obtained for isolated clusters, consist of non-evolving single- mass stars.

We have found that $SFE_{gl} = 0.3$ is sufficient to save almost all stars ($> 80\%$) and keep the cluster compact after violent relaxation. The model cluster with $SFE_{gl} = 0.13$ does not survive the instantaneous gas expulsion when the IMF and the stellar evolution are introduced in the simulations. The $SFE_{gl} = 0.15$ model cluster survives the instantaneous gas expulsion, although with a small final bound fraction.

The stochastic effect is high in low SFE clusters due to low number of high-mass stars [20]. Therefore in the next study we plan to consider more random realizations and study the stochastic effects due to the mass-function in more detail. We do not consider any effect from dark matter due to relative small scales [27].

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ОҚШАУЛАНҒАН ЖҰЛДЫЗДЫҚ ШОҒЫРЛАРДЫҢ ҚАРҚЫНДЫ РЕЛАКСАЦИЯСЫ

Аннотация. Осы жұмыста бастапқы масса функциясы мен жұлдыздар дамуының жұлдыздық шоғырланудың лездік газ ығыстырылуынан кейінгі сақталуына әсері қарастырылады. Жұлдыз түзілуінің тиімділігі (ЖЖТ) жергілікті тығыздықпен анықталатын модельге сәйкес, зерттеліп отырған жұлдыздық кластерлер орталық шыңға ие ЖЖТ-мен құрылады. Жұлдыз түзілуінің тиімділігі 0.13-пен 0.50 аралығында жататын жұлдыздық шоғырланулардың тікелей *N*-body модельдеуі $N_* = 10^4$ жағдай үшін орындалған.

Массаның жұлдыздар эволюциясы себебінен жоғалуы жаһандық жұлдыз түзілуінің тиімділігі жоғары ($SFE_{gl} > 0.2$) жұлдыздық шоғырланулардағы байланысқан жұлдыздар санына әсер етпейтіні, ақырғы байланысқан фракцияның массасы тек жұлдыздар дамуы арқасында (байланысқан жұлдыздар санының азаюы себебінен емес) кемитіні табылған. Алайда, $SFE_{gl} = 0.15$ төмендеу шоғырланулар жұлдыздар эволюциясынан болатын масса жоғалуының әсеріне ұшырап, массалары бірдей, эволюцияға қатыспайтын жұлдыздардан тұратын кластерлерге қарағанда байланысқан жұлдыздар саны аздау болып сақталып қалады. Оған қоса, SFE_{gl} жоғары шоғырланулар қарқынды релаксациядан кейін қатты кеңеймейтіні, ал $SFE_{gl} = 0.15$ пен 0.20 тең кластерлер – айтарлықтай ұлғайатыны алынған. Біздің модельде $SFE_{gl} = 0.30$ сияқты төмен жаһандық жұлдыз түзілуінің тиімділігі кластер газ ығыстырылу кезінде өзінің массасы мен өлшемін сақтау дерлік үшін жеткілікті болып шықты.

Түйін сөздер. галактикалар: жұлдызды шоғырлар: жалпы - әдістер: сандық- жұлдыздар: кинематика және динамика - шашыраңқы шоғырлар мен бірлестіктер: жалпы

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БУРНАЯ РЕЛАКСАЦИЯ В ИЗОЛИРОВАННЫХ ЗВЕЗДНЫХ СКОПЛЕНИЯХ

Аннотация. В работе исследуется влияние начальной функции масс и звездной эволюции на выживаемость изолированного звездного скопления после мгновенного выдувания газа. Исследуемые модельные кластеры образуются с профилем эффективности звездообразования (SFE), имеющим центральный пик, в соответствии с моделью формирования кластеров, в которой эта эффективность определяется локальной плотностью. Было выполнено пря- мое N -body моделирование звездных скоплений с $N_* = 10^4$ и глобальной эффективностью звездообразования, лежащей в диапазоне от 0.13 до 0.50.

Было обнаружено, что потеря массы за счет эволюции звезд не влияет на конечное число связанных звезд в звездных скоплениях с высокой глобальной эффективностью звездообразования ($SFE_{gl} > 0.2$), и конечная масса связанной фракции уменьшается только из-за звездной эволюции (не из-за уменьшения числа связанных звезд). Однако звездные скопле- ния с более низкой глобальной $SFE_{gl} = 0.15$ больше подвержены влиянию потери массы за счет звездной эволюции и выживают с меньшим числом звезд, чем скопления, состоящие из неволюционирующих звезд одной массы. Также скопления с высокой SFE_{gl} не расширяются сильно после бурной релаксации, тогда как кластеры с SFE_{gl} = 0.15 и 0.20 значительно расширяются. В нашей модели такой низкой глобальной эффективности звездообразования, как $SFE_{gl} = 0.30$, оказывается достаточно для того, чтобы кластер почти сохранил свою массу и размер во время вытеснения газа.

Ключевые слова. галактики: звездные скопления: общие - методы: численные - звезды: кинематика и динамика - рассеянные скопления и ассоциация: общие

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