Stellar mass loss and the fate of star clusters

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Abstract

It is generally believed that most (if not all) stars are born in clusters. Nevertheless, we see most stars in the night sky as single stars or binary systems, not in clusters. This is an indication that most star clusters disrupt on short timescales. A favorite candidate mechanism responsible for this destruction of clusters is the removal of the residual gas (after star formation) by the ionizing radiation, strong stellar winds and supernovae of the massive stars in the cluster. Cluster dynamics will be discussed with emphasis on the first 10 Myr and the role the massive stars can play will be highlighted. With the use of simulations more realistic scenarios can be investigated. It will become clear that massive stars can indeed easily destroy most of the stellar clusters in their early days, creating the huge field star population we observe in most galaxies.

1 Introduction

The main visible constituents of our universe are the stars. The light we recieve from other galaxies mainly comes from stars inside them and our night sky is filled with pointlike sources, sometimes even so many that we see them as a vague band of light, our Milky Way Galaxy. We see most of the stars as field stars, i.e. not in clusters, but mainly as binary or multiple system or as single stars.

On the other hand, in star formation regions we mainly see clusters of stars being born. It is generally believed that the vast majority of stars is born in clusters (if not all, see e.g. Larsen (2004)). This hints to a scenario in which stars are born in clusters, followed by the destruction of the clusters, resulting in a field star population.

Indeed, in many galaxies it is found that star cluster in the first years of their existence undergo a period of childhood deceases, in many cases followed by death. The infant mortality rate sometimes seems to be higher than 80% (Bastian et al. (2005); Lada & Lada (1991); Tremonti et al. (2001); Lamers et al. (2005)). In this paper I will review the effects of stellar mass loss on the evolution of a cluster and show that this probably is the main cause of this infant mortality of star clusters.

This paper is structured as follows. The following section (section 2) will give an overview of observations that show evidence for the removal of gas from a young cluster as well as analyses of extragalactic cluster populations in which clear indications of high infant mortality rates are visible. Next (section 3), a brief overview of cluster dynamics is given, paying attention in particular to the timescales involved. The following section (4) contains a discussion of cluster parameters, leading to disruption on small timescales. In section 5 stellar mass loss, on timescales of early cluster evolution, is described and relevance to cluster infant mortality is discussed. Dynamical simulations of star clusters, in which stellar mass loss is modelled, are described in section 6. The final section (7) gives a summarizing overview.

2 Observations

In this section I will describe several kinds of observations related to stellar mass loss and the disruption of clusters. First a simple overview of images, where we really see the outflowing gas around or partially inside clusters, or complexes of clusters. This will then be followed by a brief review of the studies to extragalactic cluster populations. In these studies the age distributions sometimes give clear indications of high infant mortality rates.

2.1 Imaging

In our own Milky Way galaxy we find lots of star forming regions, all of different ages. We therefore have snapshots of cluster evolution of the clusters that are born inside them. One example is the Orion Nebula (Fig. 1). The trapezium cluster contains some very massive stars (the trapezium itself). The 'hole' in the interstellar matter, just around the center of the cluster is a consequence of the UV radiation of the young hot and blue stars. Together they make up a superbubble (bubble is used for a bubble around a star, whereas a superbubble usually means the merger of several stellar bubbles, e.g. around a cluster) around the cluster. If there are lots of clusters formed in regions with high star formation rates (e.g in interacting galaxies) they tend to form in groups, the so-called 'complexes' Here we can even see 'supersuperbubbles', the merged superbubbles of all the clusters inside the complex; see Fig. 2.

From these images of (complexes of) clusters it is clear that clusters do lose a considerable amount of gas. As will be-

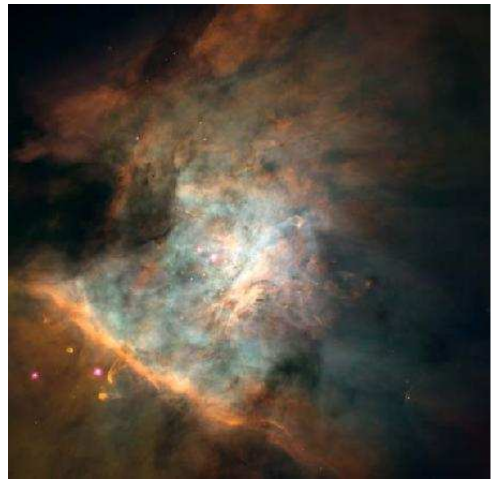

Figure 1:
The Orion nebula (M42) is a star forming region in our Milky Way. We can see the trapezium cluster being born. The 'cave' in the ISM is blown by the radiation and stellar winds of the massive stars in the cluster.

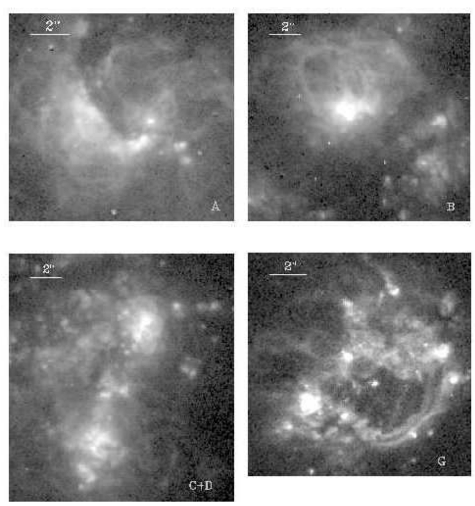

Figure 2:
In the Antennae galaxies (NGC4038/4039, see Whitmore et al. (1999)) one clearly sees complexes of clusters (clusters appear as bright spots on these distances) surrounded by a superbubble, blown by the massive stars inside them. These images are taken with the Hubble Space Telescope in Hα.

come clear in section 4, the loss of gas (mass) can unbind the cluster, leaving behind a group of stars which are no longer gravitationally grouped together. They are supposed to fly apart, leaving a smaller cluster (the core of the parent cluster) or nothing at all.

2.2 Analysis of cluster populations

If this is a correct picture, there should be more young clusters than old clusters (assuming a constant formation rate), because the clusters are likely to be disrupted on timescales, comparable to the main sequence lifetimes of massive stars ($\sim 10^7$ yr). Bastian et al. (2005) used a method described in Bik et al. (2003) (and references therein) to determine ages, masses and extinction for the clusters in the central region of M51 with the use of multiwavelength broadband photometry. They found the age distribution that is shown in the left-hand panel of Fig. 3. They plotted the age distribution (number of clusters in a certain age bin) and the cluster formation history (number of newly born clusters per Myr as a function of age) for three different mass intervals. A few things are important when examining this kind of figures. A first is the fact that clusters fade as they age, due to stellar evolution (and possibly to the loss of stars), see e.g. de Grijs et al. (2003); Bik et al. (2003). Therefore younger clusters are brighter and more easily detected. For the same reason, more massive clusters are easier to detect as well. Lots of uncertainties in the determination of cluster parameters from broadband photometry are thoroughly investigated by de Grijs et al. (2003).

In the range $\log(M/M_{\odot}) > 4.7$ the sample is complete up to ages of 1 Gyr. The increase in formation rate at ~ 60 Myr is due to the last interaction of M51 with its companion (NGC 5195) (Salo & Laurikainen, 2000). From the increase at young ages (few Myr) in the right-hand panels it might appear that M51 is going through a period of bursting star formation right now. Another possibility is that the clusters younger than 10 Myr will disrupt in the next few Myr.

In the first place there is no reason why there should be a burst of star formation at the present epoch. Secondly, this possible early disruption is also found in the Antennae (end of this section and Whitmore (2003)), the open clusters in our own Milky Way (Lada & Lada, 1991) and in NGC 5253 by Tremonti et al. (2001). Assuming it is a high infant mortality rate that causes the cluster formation rate to show a downturn in the observations, we can now investigate the expected percentage of clusters that will be disrupted soon. One note: the conclusion that this downturn is caused by disruption also makes the term 'formation rate' given to the right-hand panel of Fig. 3 a bit inappropriate: it is the formation rate convolved with the disruption rate.

Comparing the bins $6.6 < \log(t/\mathrm{yr}) < 6.93$ and $6.93 < \log(t/\mathrm{yr}) < 7.26$ one finds an expected disruption percentage as a function of cluster mass as shown in Fig. 4. Two things strike the eye. In the first place the expected percentages are high: 50 - 80%, but the errors are large. Secondly: there seems to be no mass dependence of this disruption rate at all, in sharp contrast to observations and theoretical considerations of 'normal' cluster disruption (i.e. the slow disruption resulting from N-body dynamics) of e.g Boutloukos & Lamers (2003) and numerical investigations of e.g. Baumgardt & Makino (2003); Fall & Zhang (2001); Vesperini (1998).

Following Fall et al. (2005) in their investigation of the Antennae (NGC 4038/4039, see also Whitmore et al. (1999)) one can see the same effect there. For three different samples of clusters in this pair of interacting galaxies the 'formation rate' is plotted against age, see Fig. 5. The luminosity-limited sample (open symbols) is steeper than the mass-

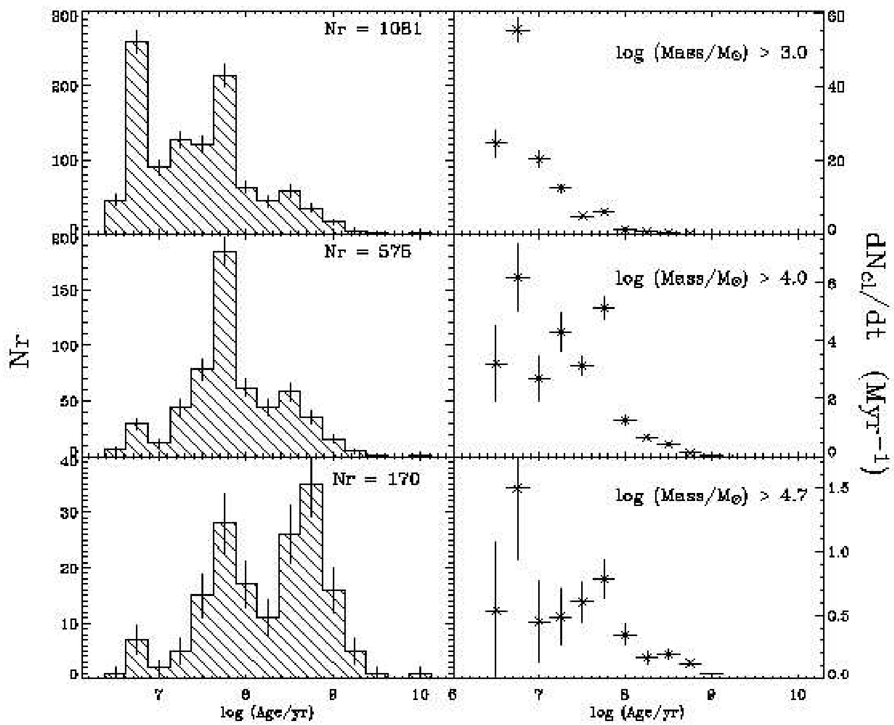

Figure 3:
The age distribution (number of clusters per age bin: left) and formation history (number of newly formed clusters per Myr as a function of age: right) of star clusters in M51 as determined by Bastian et al. (2005). Different mass ranges are chosen. It is clear that this biases the interpretation.

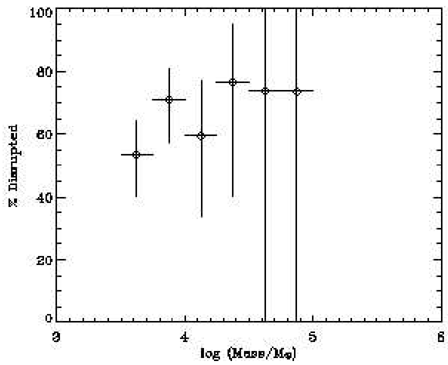

Figure 4:

By comparing the agebin left of 10 Myr to the bin right of that in Fig. 3 one is able to predict which fraction of the clusters will disrupt in the coming few Myr, dependent on mass. The result is shown: percentages range from 50 -70% and seem to be independent of mass.

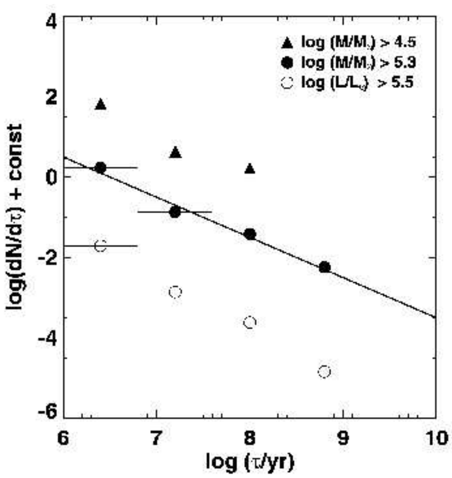

Figure 5:

Mass- as well as luminosity-limited samples of clusters in the Antennae, plotted similar to the right-hand panel of Fig. 3. Open symbols correspond to luminosity-limited samples, which are steeper than the mass-limited distributions. The mass-limited samples (limited on a different mass) are not significantly different again. The vertical ofset is the result of an arbitrary constant added (and subtracted) to (and from) the points, in order to see them clearly seperated.

limited samples (filled symbols), because that sample contains a higher proportion of young clusters. The mass limits are indicated in the plot. The triangled sample is also present in the sample indicated with circles (note that there is a random constant applied in order to see the three samples clearly seperated). Of course the argument of non-bursting star- or cluster formation does not apply for the Antennae, because these systems are in severe interaction. Despite that, we can say that we see a mass independent disruption here as well. The argument here is that this system is interacting for already a few $\times 10^8$ yr, which is much longer than the median age of clusters (few $\times 10^7$ yr). A second reason is that the age distribution is similar in different parts of the galaxy, some of which appear to be interacting more strongly than others. So, in Fig. 5, the dots at almost 10^9 yr are supposed to be the 'normal' cluster formation rate, before the interaction. The other three points are all datapoints of clusters which are formed *during* the interaction. The apparent decrease in formation rate (stronger in difference between the first two bins than in the second two) can be explained by the infant mortality of the clusters.

The fact that two different (types of) galaxies both show a mass independent disruption in the first 10 Myr, whereas 'normal' cluster disruption is supposed to be mass dependent (disruption time proportional to the mass of the cluster to the power 0.6 (Boutloukos & Lamers, 2003; Baumgardt & Makino, 2003; Fall & Zhang, 2001; Vesperini, 1998)), it is proposed that this infant mortality rate is a fundamentally different disruption process than e.g. two-body relaxation or tidal stripping by their host galaxies.

Although from observations it is clear that clusters are depleted from their residual gas on rather short timescales and that most clusters disrupt on timescales of about 10 Myr it is as yet not very well understood from the dynamical point of view. The next few sections will deal with cluster dynamics and stellar mass loss in order to show the results of simulations of star clusters afterwards.

3 Cluster dynamics

Although real clusters do not live in isolation, but rather in a galaxy with an irregularly structured gravitational/tidal field and lots of other clusters and Giant Molecular Clouds, I will mainly discuss isolated clusters in this paper. I will do so in order to clearly distinguish between evolutionary effects that are caused by external effects (such as tidal stripping and disk shocking) and internal effects (gravitational interaction between stars in the cluster and the effects of stellar evolution). By excluding external effects, the only contamination of dynamical effects come from few-body interactions in the dense cores (and less frequently of course also in their outer halo) and it should be much easier to focus on the effects of stellar mass loss (two or more body relaxation is a much slower process anyway). For thorough discussions of cluster dynamics see Heggie & Hut (2003) and Binney & Tremaine (1987); here I will only give a brief review of isolated cluster evolution. In the next section I will further focus to the first ∼10 Myr, the era in which the most violent stellar mass loss (section 5) takes place.

In a star cluster all stars move around with all different velocities. The average time it takes a star to cross the cluster is called the crossing time of a cluster and a simple expression for it is:

$$\tau_{\mathrm{cr}} = \frac{2R}{\sigma} \tag{1}$$

In which R is the radius of the cluster and σ its velocity dispersion, given by

$$\sigma = \sqrt{\frac{2}{5}\frac{G\left(M_{\mathrm{star}} + M_{\mathrm{gas}}\right)}{R}} \tag{2}$$

Here it is assumed that the cluster is in virial equilibrium (note: *not* in dynamical equilibrium!), therefore having a more or less Maxwellian distribution of stellar velocities with this one-dimensional dispersion. For completeness and future reference I included both stellar mass and mass in the form of gas that together make up to the total gravitational field.

Because of few-body interactions the massive stars (and binaries) will 'sink' into the star clusters core. The less massive stars (which gain energy during few body interactions) speed up, and they populate the outer regions of a star cluster. As soon as they, in whatever way, obtain a velocity higher than the escape velocity,

$$v_{\mathrm{esc}} = \sqrt{\frac{2GM_{\mathrm{total}}}{R}} \tag{3}$$

they are likely to escape from the cluster. The gradual removal of low mass stars is what is called 'evaporation' of a cluster. Every cluster is intrinsically unstable due to this effect (even if a cluster would have lived on his own in an entirely empty universe, it would gradually disperse). Ofcourse, removing stars lowers the gravitational potential of the cluster, reduces the escape velocity and therefore this is a runaway effect (although slow).

Disruption processes are accelerated when the cluster is in gravitational interaction with any other object (the whole galaxy, other clusters, GMC's), but the above described processes will make sure that a cluster will dissolve anyway.

4 Early disruption of star clusters

With the huge field star population and the comparatively low number of old clusters observed as arguments for a high infant mortality rate, I will here discuss models that explain fast disruption modes for star clusters. It is meant to get a qualitative feeling for cluster disruption as a result of gas removal.

It is easy to see from Eq. 3 that if the mass of the cluster suddenly reduces by a non-negligable factor, the escape velocity will also be reduced. Therefore, the high velocity tail of the velocity distribution will contain a large fraction of stars with a velocity above the escape velocity. Within a crossing time, a large fraction of these stars will be removed from the cluster. The velocity distribution will only adjust itself on timescales of the relaxation time (the time it takes a cluster to get back in pseudo-equilibrium after a perturbation, or the time in which a cluster 'forgets' about its past), which is of the order of a Gyr (Heggie & Hut (2003)).

When stars are formed, the effeciency (SFE) will not be 100%. Therefore some part of the original cloud the cluster formed from, will remain between the stars. This gas can in total make up a considerable amount of mass, contributing to the gravitational potential of the cluster. If this gas can be removed suddenly, this will provide a likely process to disrupt star clusters. In the early evolution of star clusters it is clear that the star formation efficiency and the timescale of gas removal from the cluster are two basic parameters. We can make a zero order approximation for a constraint on the SFE. If we assume fast gas dispersal: $\tau_{\mathrm{g}} < \tau_{\mathrm{crossing}}$ then the instantaneous velocity dispersion (which only changes on a crossing timescale) is still determined by the total amount of mass (stars *and* gas), while the 'new' escape velocity is only determined by the mass that is captured in stars. The cluster will become unbound if the velocity dispersion (eq. 2) exceeds the new escape velocity (eq. 3, with the total mass being the total mass in stars), and it is easily concluded that a cluster needs a SFE of at least 50% to remain bound under these conditions.

If the removal of gas is not instantaneous, but rather smooth it can be expected that the constraints on the SFE in order to remain bound are less severe. If a cluster loses a bit of its residual gas, but not all, it can remain bound. In the next few crossing times it will adjust its velocity distribution (and dispersion) towards the new situation. The cluster does not need a whole relaxation time (which for massive clusters is much longer than a crossing time (Binney & Tremaine, 1987)), because also for a non-total adaption to the new situation the dynamics can be such that at least a part of the stars stay bound and the removal of the gas results only in a smaller cluster, instead of total dissolution. After the removal of all the gas it will probably have lost stars as well, but it is by far impossible that a substantial amount of stars are still bound in the cluster, even if the SFE was lower than 50%. Quantitatively, this will be discussed with the help of numerical simulations in section 6.

5 Stellar mass loss

It will have become clear that the main stellar mass loss mechanism we have to care about, are those mechanisms that act on a short timescale after star formation and that put sufficient energy and momentum into the residual gas to drive it out.

5.1 Energy input by massive stars

We must, though, not only concentrate on the stellar winds, but we should rather take a look at ionizing radiation as well. Hot young stars emit a lot of UV radiation and the photo-ionization of the gas may heat it and that heating may cause gas to be evaporated out of the cluster as well. A typical O5 star produces some $4 \cdot 10^{52}$ erg of UV radiation over its lifetime of about 10^7 yr. This will be able to remove about $10^{3\,\text{à}\,4}\ M_\odot$ of gas (Chiosi & Maeder, 1986). For more massive gas remainders only the inner part will be ionized and almost no gas at all will be lost.

A simple estimate of the number of OB stars needed to expell residual gas from the cluster purely by ionizing radiation is given by Geyer & Burkert (2001). They conclude that, with ϵ the star formation efficiency a number of $(1-\epsilon)^{10/7} \cdot 1.3 \cdot 10^2$ O and B stars are enough to ionize all the gas from an analytical approach using typical molecular cloud densities and temperatures. They compare the size of Strömgren spheres of multiple OB stars together as a function of time and compare that size with the size of the cloud the cluster forms from. They find that with the given number of stars the cloud can be completely ionized.

For clusters that do not satisfy this number of massive stars, the strong stellar winds of massive stars will have to be taken into account. Already after a few Myr (at most) the massive young stars blow strong stellar winds, as is intensively discussed in Lamers & Cassinelli (1999). These stellar winds are line driven winds with high terminal velocities (a few thousand kilometers per second) and high mass loss rates (typically $\sim 10^{-5}\ M_\odot \mathrm{yr}^{-1}$). To take the O5 stars again as a (quite extreme) example: these stars add around 10^{49} erg to the interstellar medium (at typical globular cluster metallicities, see e.g. Kudritzki et al. (1987)), whereas the typical binding energy of a globular cluster is about 10^{53} erg.

If the ionizing radiation and the strong stellar winds would not have been enough, the job can be completed by the supernovae. The typical potential energy of the outflowing material, liberated in a supernova is 10^{51} erg (the rest of the energy mainly comes out in the form of neutrinos). In these explosions, the remainder of the interstellar gas will be driven out, leaving most of the clusters unbound. It should first be noted that only a few percent of the supernova energy will be put into the interstellar gas (Goodwin et al., 2001). So, although typical supernova energies are comparable to the binding energy of a cluster, several supernovae may be needed to fully disrupt a cluster. In most clusters there are indeed several (or several tens of) stars with masses $> \sim 8$ $M_\odot$ available to do the job.

5.2 Can stars destroy their parent cluster?

We are now able to make an estimate of the total enery input of stars as a function of the total mass of the cluster, the star formation efficiency and the stellar initial mass function. This can then be compared to the binding energy of the gas in the cluster in order to see whether this input is enough to deplete the cluster of gas or to the total binding energy of the cluster to see whether the stars are able to blow the cluster apart.

To remove all of the gas, the energy input by the stars should be at least equal to the potential energy of the gas:

$$E_{p,g} = G\frac{(1-\epsilon)M_{\mathrm{total}}^2}{R} \tag{4}$$

This energy can be put in by three factors: UV radiation, winds and supernovae. The total energy input by stars can then be written like

$$E_{\mathrm{in}} = E_{\mathrm{UV}}N_{\mathrm{UV}} + E_{\mathrm{wind}}N_{\mathrm{wind}} + E_{\mathrm{SN}}N_{\mathrm{SN}} \tag{5}$$

In this equation, E means a typical energy of the indicated source for stars and N is the number of stars that is important in this process. This number can in general be expressed in the total mass of the cluster and the star formation efficiency, making use of the minimum mass a star needs to be an important source of energy. The rest of this therefore is an order of magnitude estimation. Note that the total binding energy of the cluster is of the same order of magnitude as the gravitational energy of the gas, as long as the star formation efficiency is not too small (say, above $\sim$10%).

In general it can be stated that the number of stars for a source of energy input to the cluster can be written

$$N_X = C \cdot \int_{m_X}^{\infty} m^{-2.35}\mathrm{d}m \tag{6}$$

In here a stellar initial mass function like Salpeter (1955) is assumed, with a lower stellar mass limit of 0.2 $M_\odot$. N_X denotes the number of stars responsible for a particular form of energy input (UV, winds, or supernovae) and m_X is the minimum stellar mass required for that particular energy input mechanism. The integration constant C comes from the total mass of the cluster and the star formation efficiency:

$$\epsilon M = C \cdot \int_{0.2}^{\infty} m^{-1.35} \mathrm{d}m \qquad (7)$$

and we find that

$$N_X = 0.15 \cdot \epsilon \cdot M_\mathrm{t} \cdot m_X^{-1.35} \qquad (8)$$

Here, $M_\mathrm{t} = M_\mathrm{total}/M_\odot$ is the mass of the cluster (including gas as well as stars) in solar masses.

In this estimate I will concentrate only on the stars of $> 8\,M_\odot$, for these will explode in a supernova and have a fast enough evolution to possibly have an important effect on the cluster as a whole, during the first 10^7 yr. This means that all N_X can be put on the same value, if we choose appropriate mean values for the energy input of any of the three input mechanisms. So:

$$N_X = 0.01 \epsilon M_\mathrm{t} \qquad (9)$$

The total energy input (Eq. 5) is given by

$$E_\mathrm{in} = 0.01 \epsilon M_\mathrm{t} \cdot (E_\mathrm{UV} + E_\mathrm{wind} + E_\mathrm{SN}) \qquad (10)$$

Using the values for the input energies mentioned before (including the fact that only a few percent of this energy goes into the ISM), the total energy input of a single massive star (the sum in brackets) is about $5 \cdot 10^{50}$ erg. Using this value and equating Eqs. 10 and 4 we find

$$5 \cdot 10^{48} \epsilon M_\mathrm{t} = G \frac{(1-\epsilon) M_\mathrm{total}^2}{R} \qquad (11)$$

Converting this back to the same units:

$$2.5 \cdot 10^{15} \epsilon = G \frac{(1-\epsilon) M_\mathrm{total}}{R} \qquad (12)$$

We can see that this equation is not independent of the cluster mass. It should not be: the number of massive stars is proportional to the mass of the cluster, whereas the binding energy of the cluster is proportional to its square. Using again very typical values for globular clusters (i.e. $M \approx 10^5\ M_\odot$, $R \approx 3$ pc), we find that the SFE should be about 99% in order to keep the cluster together. It therefore now seems reasonable that a cluster that survives its 10 Myr childhood is an exception, rather than a rule.

5.3 Timescales of gas removal

As already noted in section 4 the timescale of gas removal from the cluster might play an important role. We will also see this in the simulations described in the next section. Here a brief overview of the dynamics of the outflow will be given, considering the winds, the interaction of these winds with each other and the interaction with the interstellar medium.

The theory of interacting stellar winds is intensively discussed in Chapter 12 of Lamers & Cassinelli (1999). The stars loose mass at a certain mass loss rate and velocity. This wind material is accelerated (in the case of the wind of a massive star during its lifetime, before supernova) up to terminal velocoties of a few thousand kilometers per second. As soon as this wind runs into the ISM, sweeping up the IS material, the momentum of the wind has to be shared with the swept up material. A shock emerges at the interaction region, moving outward with a much lower velocity. This shock region is visible as a spherical (or less symmetric, depending on the properties of the central star and the distribution of ISM around the star) shell around the star. Because this ISM material is more or less homogeneuos, with a density that is not going down on average with the distance to the star (as for example in the case of the interaction of the fast and the slow wind in the formation of a planetary nebula, see Lamers &

Cassinelli (1999)), the ISM mass piling up in the shell is getting more and more.

Normally, the evolution of such a growing bubble can be divided into three phases. The first phase (the freely expanding phase) is a phase in which the material is not really affected by the swept up, low density material. In a cluster that formed from a molecular cloud and only about half of the mass is converted into stars, the ISM is not at all that teneous. Using the relation 12.5 from Lamers & Cassinelli (1999) this phase will last about 10 years. In this time (in which the shock region travels with nearly the terminal velocity of the wind) it grows to about 10^{-2} pc. With a star density of 1000 pc^{-3}, the mean distance between stars is ∼0.1 pc. At this point the different stellar winds are not yet aware of each other *if they turn on their winds at the same time.*

After the freely expanding phase, the bubble goes through another short phase: the adiabatic phase. During the adiabatic phase the bubble expands adiabatically. The heated material in the shock (already heated in the freely expanding phase) cools because there is work done to expand the bubble. At a certain temperature (10^6 K) radiative cooling through lines becomes important. The shell will then rapidly cool to 10^4 K, and we therefore say that this adiabatic phase ends as soon as the the shocked material has a temperature of 10^6 K. This phase has then last about 6 times the duration of the freely expanding phase. This again is fairly short, but the bubbles of the different stars are now starting to fill a non-negligable space between the stars (a few percent, only a small fraction of the stars actually produce these bubbles).

The snowplow phase, then, is the final and longer lasting phase which is approximately started when the different bubbles merge and form a 'weblike' structure (eventually forming the superbubble), with teneous fast wind in between the merging, high density, line radiation emitting, shocked regions. As Chu et al. (2004) point out, theoretical modelling and observations of superbubbles are not yet in good agreement. For the physical parameters of these superbubbles I will therefore only look at observations.

Whitmore et al. (1999) measured outflow velocities in the Hα bubbles (visible in Fig. 2) in the Antennae having a velocity of 25 - 30 km s^{-1}, comparable to the escape velocity of a typical cluster of ~ 15 km/s (see Eq. 3, for a 10^5 $M_\odot$, 3 pc cluster $v_{\rm esc}$ = 17 km/s). Similar results are found by other authors, e.g. Oey (2004). For a cluster with a radius of 4 pc this corresponds to an evacuation time (radius of the cluster divided by the speed of the stellar wind) of only 0.2 Myr, comparable to crossing times of a 10^5 $M_\odot$ cluster, fast enough to a have a deadly impact on the dynamical evolution of the cluster.

In the following section simulations of young clusters with stellar mass loss will be described, including UV radiation, stellar winds and supernovae, in order to get a better quantitative view on the impact of stellar mass loss on star cluster dynamics.

6 Simulations of disrupting star clusters

One of the first attempts to model star clusters in their early life, taking into account the (removal of) residual gas, SFE and other parameters (that we are not concerned with here) is made by Goodwin (1997). In his N-body simulations the removal of the gas is either caused by supernovae or by the cumulative effect of ionizing radiation and stellar winds. Because his work is done with a fixed number of particles (each representing 'groups' of stars) the results are not really illustrative, and therefore I will here describe the work of Geyer & Burkert (2001).

As a first approximation they describe the residual gas as an external potential. They model their clusters with King (1966) profiles. The loss of gas is assumed

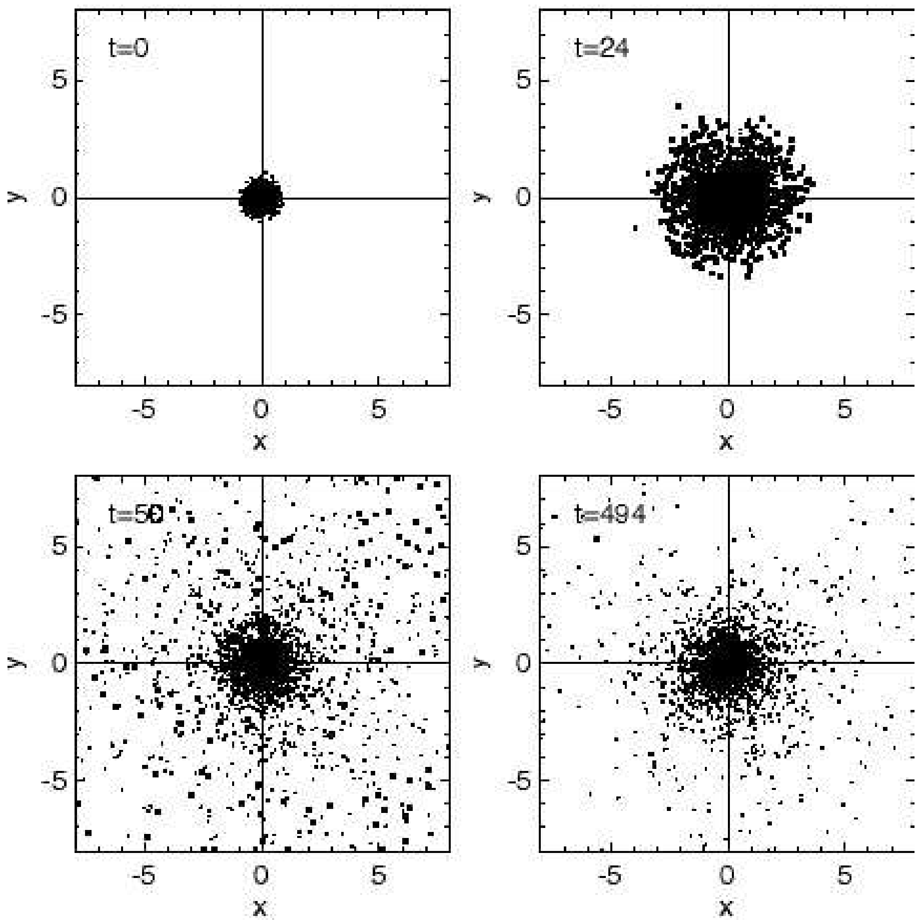

Figure 6:
An example of an N-body simulation of Geyer & Burkert (2001) containing 4000 equal mass stars. The SFE is 40%. The units of time indicated are such that the gas expulsion is turned on at $t = 20$ (8.4 Myr) and lasts for $t_{\rm exp} = 2$ (0.84 Myr, see text for the scaling of the time units). The dots indicate stars, the squares are unbound stars that eventually escape.

to be linear in time, starting at a certain time t_0, lasting a gas expulsion time $t_{\rm exp} = R_t/a$, in which R_t is a typical cluster radius (the tidal radius of a King profile) and a is the isothermal sound speed in molecular cloud gas of $T = 10$ K. As an example, Fig. 6 shows a result of an N-body run, with a star formation efficiency of 40%, an initial king concentration parameter (W_0) of 5.0. The units of time indicated are such that the gas expulsion is turned on at $t = 20$ and lasts for $t_{\rm exp} = 2$. This unit of time is scaled to 3.5 times the crossing time at the half mass radius ($= 1.5 \cdot 10^6$ yr for a $10^5\ M_\odot$, 10 pc cluster). Stars are called unbound (and drawn with a rectangle) if their total energy (kinetic plus potential) is positive.

It might seem that this cluster (even with a SFE of only 40%) survives the gas expulsion. It has to be said here that although there is indeed a small cluster left, this cluster lost 90% of its stars because of the gas loss.

In Fig. 7 for a whole series of N-body runs the SFE is plotted against the fraction of stars that is still bound (long) after gas expulsion. Different types of lines represent different initial cluster profiles, different symbols represent different gas expulsion times. It is clear that the fraction of stars left in the cluster depends quite strongly on the gas expulsion time (at given SFE, the difference is given mainly by the difference in $t_{\rm exp}$). A slower gas expulsion can lower the SFE needed to sustain a bound cluster, as expected. The cluster profile is not important; for a given SFE and gas expulsion time the results for all cluster profiles are similar. The most important factor seems to be the SFE. At given gas expulsion time, the fraction of bound stars left is a very sensitive function of the SFE, as can be seen from the steeply rising lines.

In reality it is to be expected that the SFE and gas expulsion time are related to each other: if more gas is left, it will take longer (more energy and momentum) to drive it all out, but there are less stars to do it (because of the lower SFE).

More realistic simulations are carried out by Fellhauer & Kroupa (2005). Because of the normal cluster relaxation, clusters will evolve further and loose stars after gas expulsion, so a 'final' fraction of bound stars is hard to define. Instead they plot the fraction of bound stars after 1 Gyr (Fig. 8). Note that this is infant mortality, followed by the 'normal' dissolution of clusters! They performed three random

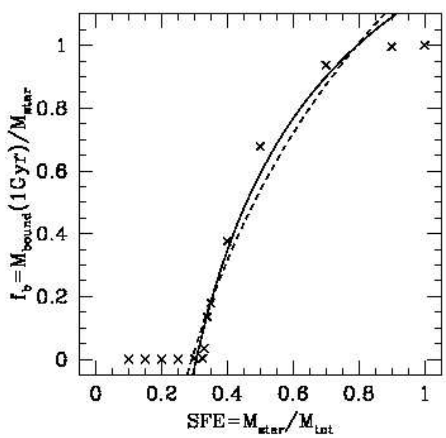

Figure 8:
Average results of 3 Monte Carlo simulations of Fellhauer & Kroupa (2005). The star formation efficiency (in the usual definition) is plotted against the fraction of bound stellar mass after one Gyr to the initial stellar mass. The crosses are the averages of the simulations, the dashed line is a logarithmic fit, $f_b = \ln({\rm SFE}) + 1.23$, the solid line is a power law fit, $f_b = -{\rm SFE}^{-0.65} + 2.16$.

realisations of a star cluster loosing gas, with a given SFE. All clusters were Plummer spheres (positions and velocities according to a Plummer distribution function) with the same radius. The shape is very similar to the results of Geyer & Burkert (2001). Very similar conclusions are also drawn by Boily & Kroupa (2003).

Using N-body simulations it can be shown that the constraints on the SFE are not as severe as it seemed from the very simple analytical description given in section 4. Because of the finite time it takes

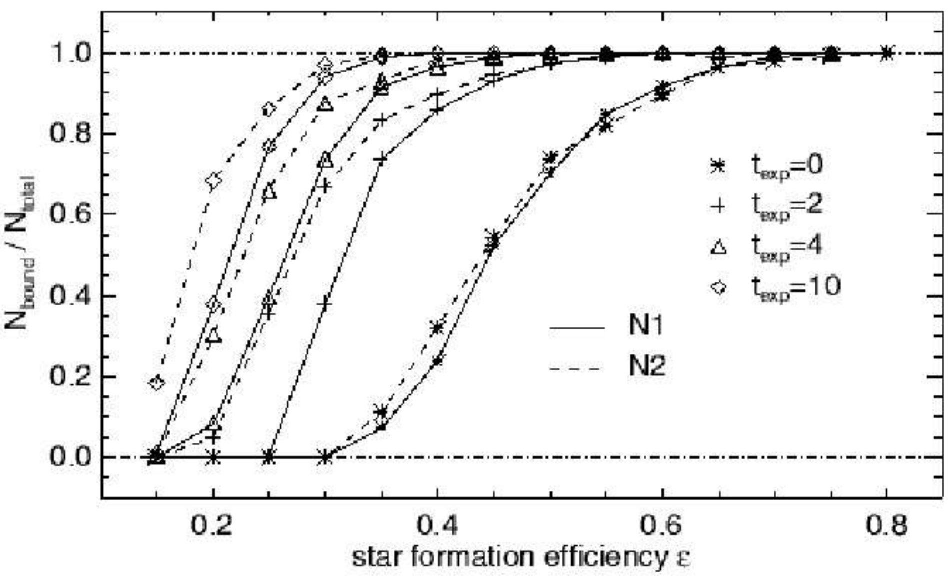

Figure 7:

Series of N-body models of Geyer & Burkert (2001). The ratio of bound stars after gas expulsion to the total initial number of stars is shown as a function of the star formation efficiency. Different types of lines represent different initial cluster profiles, different symbols represent different gas expulsion times, every time scaled to the crossing time at the half mass radius of the cluster, as described in the text.

the massive stars to expell the residual gas the SFE does not need to be as high as 50% in order to sustain a bound stellar cluster. On the other hand, clusters with a star formation efficiency of more than 50% may be (partially) disrupted as well, depending on the expulsion time of the gas and the remaining cluster mass (less massive clusters disrupt faster in the pure N-body phase of disruption). Keeping all the stars bound to the cluster is a very unlikely situation, mainly because SFEs are not supposed to be as high as 80% or more, as is needed to keep all of the stars bound according to the shown simulations.

The infant mortality rate is thus supposed to be high. A relation with mass is expected to exist, with the use of the arguments in section 5.1. It is hard to give precise values, because little is known about realistic SFE's, but numbers like 80% for the infant mortality rate will probably not be extreme.

7 Concluding overview

Most, or all, stars are born in star clusters. That is the conclusion we draw from observations of star forming regions, where we see groups of clusters (complexes) being born. Nevertheless a huge field star population is what makes up the most important constituent of most galaxies. Somehow these star clusters must be destroyed on a rather short timescale to understand this discrepancy.

We have seen that observations of star clusters in our own Milky Way Galaxy, as well as star clusters in other galaxies are loosing gas, simply by looking at the pictures taken of them. We see (super-) bubbles around them indicating that there is gas flowing out of the cluster, that interacts with the ISM in and around the cluster. We have also seen that clusters are most likely subject to a high infant mortality rate. In as well the Antennae galaxies as in M51 as in our own Milky Way the number of young ($<$ 10 Myr) clusters (per age bin) exceeds the older ones, sometimes even by factors of 10.

In a very simple way I have described how the loss of mass (in this case in the form of gas) can be responsible for the premature death of a star cluster. Losing mass means lowering the gravitational potential. If this happens on a timescale shorter than (or comparable with) the relaxation time of a cluster, then this will mean that a cluster cannot adapt its velocity distribution fast enough, leaving the stars with too high velocities. All stars with a positive energy (i.e. a velocity greater than the escape velocity) will be lost from the cluster. For instantaneous gas loss a simple estimation showed that a star formation efficiency of at least 50% was needed.

Numerical simultions then fine-tuned these values for more realistic situations, like non-instanteneous mass loss and the adaption of the stars of a cluster to a new physical situation. Results of this simulation revealed that the final fraction of stars that remained bound to the cluster depends indeed mainly on the SFE, but also non-negligably on the gas expulsion time. The initial cluster profile is not that important.

The conclusion of this paper is that the high infant mortality rate (and therefore the existence of an enormous field star population) can very well be due to the ionizing radiation, huge mass loss and supernova explosions of the most massive stars in clusters. It is not even very clear why there are star clusters surviving their childhood *at all*.

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