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The effect of the dynamical state of clusters on gas expulsion and infant mortality

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Abstract The star formation efficiency (SFE) of a star cluster is thought to be the critical factor in determining if the cluster can survive for a significant (> 50 Myr) time. There is an often quoted critical SFE of ~ 30 per cent for a cluster to survive gas expulsion. I reiterate that the SFE is *not* the critical factor, rather it is the dynamical state of the stars (as measured by their virial ratio) immediately before gas expulsion that is the critical factor. If the stars in a star cluster are born in a (even slightly) cold dynamical state then the survivability of a cluster can be greatly increased.

Keywords open clusters and associations: general – galaxies: star clusters

1 Introduction

The vast majority of stars form in star clusters (e.g. Lada & Lada 2003). These clusters remain embedded in their parental molecular clouds until feedback from the most massive stars removes the remaining gas on a timescale of $<$ a few Myr. The effects of this 'residual gas expulsion' on star clusters has been studied by many authors, both analytically (e.g. Hills 1980; Mathieu 1983; Elmegreen 1983; Elmegreen & Clemens 1985; Pinto 1987; Verschueren & David 1989; Boily & Kroupa 2003a), and increasingly numerically (e.g. Lada et al. 1984; Goodwin 1997a,b; Gyer & Burkert 2001; Boily & Kroupa 2003b; Goodwin & Bastian 2006; Baumgardt & Kroupa 2007).

The subject is of renewed interest as gas expulsion has been cited as the most likely cause of the 'infant mortality' of star clusters, where some $50 - 90$ per cent

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of young clusters appear to be destroyed within $10 - 50$ Myr of their formation (e.g. Lada & Lada 2003; Goodwin & Bastian 2006; see also many contributions to this volume). Interest has been further stimulated by the observations of the signature of gas expulsion (ie. an excess of light at large radii) in a number of young clusters (Bastian & Goodwin 2006).

In this contribution I revisit some of the underlying assumptions in our theoretical treatment of gas expulsion, and how it is generally interpreted.

2 The virial ratio of the stellar component

A critical star formation efficiency (SFE) of $\sim 1/3$ for star clusters to survive instantaneous gas expulsion has been determined from N-body simulations (e.g. Lada et al. 1984; Goodwin 1997a,b; Boily & Kroupa 2003b; Goodwin & Bastian 2006; Baumgardt & Kroupa 2007), and analytically (e.g. Mathieu 1983; Boily & Kroupa 2003a). These studies generally assume that the stars and gas in a cluster are in virial equilibrium *immediately before* the onset of gas expulsion. In this situation the total (stars plus gas) initial virial ratio Q_0 is

$$Q_0 = \frac{T_0}{\Omega_0} = 0.5$$

where T_0 is the total initial kinetic energy, and $-\Omega_0$ is the total initial potential energy.

For an SFE of ϵ, the virial ratio of the stars *after* instantaneous gas expulsion, $Q_\star$, is therefore

$$Q_\star = \frac{\epsilon T_0}{\epsilon^2 \Omega_0} = \frac{1}{\epsilon} Q_0 = \frac{1}{2\epsilon} \tag{1}$$

as the mass present after gas expulsion is $M_\star = \epsilon M_0$ and we assume that all other parameters (such as the structure and radius of the cluster) remain constant.

Figure 1 shows the mass loss with time for clusters with $\epsilon = 0.1$ to 0.6 from Goodwin & Bastian (2006). In agreement with other simulations these show that clusters with $\epsilon < 0.33 \equiv Q_\star > 1.5$ are destroyed, whilst clusters with $\epsilon > 0.33 \equiv Q_\star < 1.5$ are able to survive. Also note that clusters that survive may undergo significant mass-loss and their final mass may be significantly less than their initial mass ('infant weightloss', see e.g. Kroupa & Boily 2002; Goodwin & Bastian 2006; Baumgardt & Kroupa 2007).

When gas expulsion is slow (adiabatic), the effect of gas loss is less dramatic (as clusters are able to adjust to the changing potential somewhat), with a critical SFE of $\sim$ 20 per cent (e.g. Mathieu 1983; Lada et al. 1984; Goodwin 1997a; Baumgardt & Kroupa 2007). However, the assumption that the stars and gas are initially in virial equilibrium still underlies the derivation of this critical SFE in the adiabatic case.

2.1 The initial virial ratio

The dependence of survival (or mass loss) on the SFE is not, in fact, a dependence on the SFE: *it is a dependence on the virial ratio of the stars immediately before the onset of gas expulsion.* The models on which this is based assume that the stars and gas are initially in virial equilibrium and therefore translate this into an SFE. Note that gas expulsion in situations where the system (in particular the stars) are not in virial equilibrium has been considered previously (see e.g. Lada et al. 1984; Verschueren 1990).

The effective SFE (eSFE, or ϵ_e) is the SFE derived from the virial ratio of the stars (Verschueren 1990; Goodwin & Bastian 2006) is given by

$$\text{eSFE} \equiv \epsilon_e = \frac{1}{2Q_\star}$$

clearly from eqn. 1, the eSFE is equivalent to the true SFE when the stars and gas are initially virialised.

If the stars and gas are not initially in virial equilibrium (we shall discuss if this is a reasonable expectation in the next section), the survivability of clusters can be significantly altered as the eSFE is no longer equal to the true SFE.

If the stars and gas have the same (spacial) distribution then the total potential energy of the initial cluster and the potential energy of the stars will be related by the true SFE

$$\Omega_\star = \epsilon^2 \Omega_0$$

However, if we relax the assumption that the dynamical state of the stars and gas are well coupled, then we do not know the initial kinetic energy of the gas or the stars. We can define a new total kinetic energy T_{vir} which is the kinetic energy the initial (gas and stars) cluster would have *if it were in virial equilibrium*. This is not to say that the stars and gas *are* in virial equilibrium with each-other – in particular, the kinetic energy of the gas is irrelevant, as it is only the gas potential which the stars feel that is of importance to this discussion. Therefore, the true total initial kinetic energy could be anything (even sufficient to make the cluster unbound), T_{vir} is merely a mathematical tool.

If the stars have a velocity which is some fraction f of the velocity required for them to be in virial equilibrium with the potential of the gas, then the kinetic energy of the stars will be some fraction $f^2\epsilon$ of T_{vir}. It seems reasonable to assume that the fraction will depend on the SFE, and if it does not this is accounted for by f which is a completely free parameter.

By definition

$$\frac{T_{\text{vir}}}{\Omega_0} = 0.5$$

The virial ratio of the stars is

$$Q_\star = \frac{T_\star}{\Omega_\star} = \frac{f^2}{\epsilon} Q_0 = \frac{f^2}{2\epsilon} \qquad (2)$$

Comparing eqns. 1 and 2 shows that the only difference is the factor f which parameterises the initial dynamical state of the stars. If $f < 1$, the stars are dynamically 'cold', if $f > 1$ they are 'hot'.

A cluster with a true SFE of $\epsilon = 0.33$ is usually considered to be at the critical point for survival/destruction.

For a cold cluster with $f = 0.8$ and a critical true SFE of $\epsilon = 0.33$, then $Q_\star = 0.96$. Therefore the effective SFE (ie. how the cluster will respond to gas expulsion) is $\epsilon_e = 0.51$ – well into the regime of surviving gas expulsion (see fig. 1).

Conversely, for a hot cluster with $f = 1.2$ and a true SFE of $\epsilon = 0.5$ (which would be expected to survive), the eSFE is only $\epsilon_e = 0.35$ – right at the border-line of survivability.

3 Are star clusters in virial equilibrium?

More correctly this section should be titled 'Are the stars in star clusters in virial equilibrium with the residual gas potential?'. For brevity the phrase 'virial equilibrium' as used here and below refers to the virial state of the stellar component with respect to the residual gas potential.

The question of whether star clusters are in virial equilibrium can be split into two related questions.
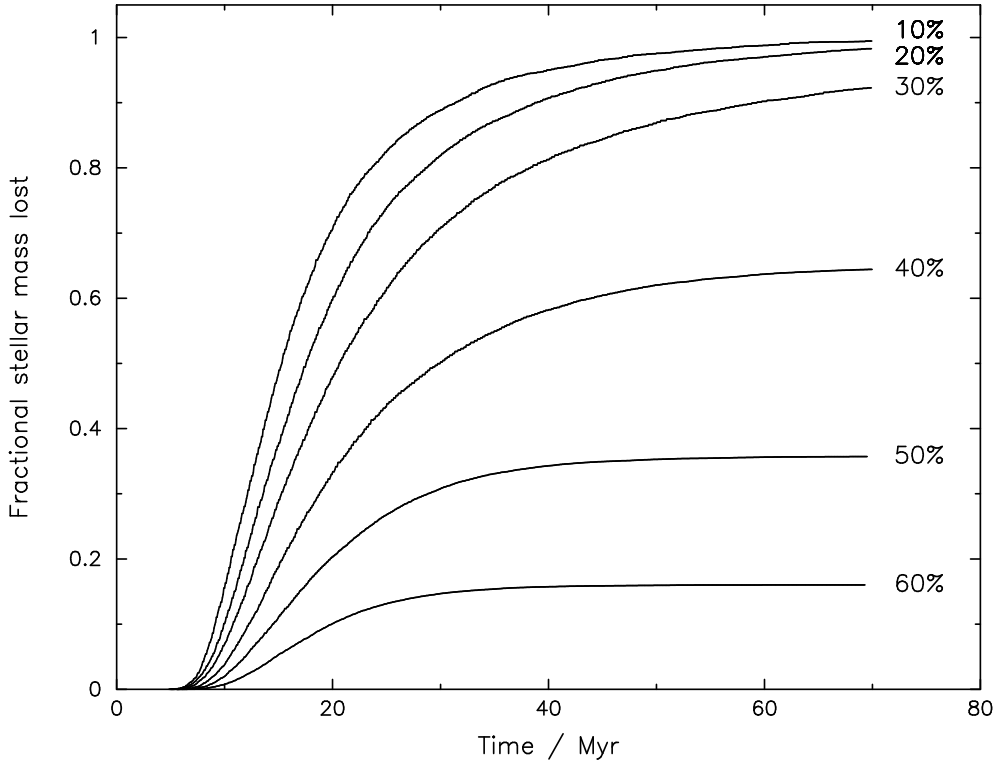
Fig. 1 The fractional stellar mass loss with time from a 20pc radius sphere around a cluster with an initial virial ratio $1/2\epsilon$, where ϵ corresponds to an SFE of 10, 20, 30, 40, 50 and 60%. From Goodwin & Bastian (2006)

Firstly, do the stars in clusters form in virial equilibrium? Secondly, and most importantly for this discussion, are the stars in virial equilibrium at the onset of gas expulsion?

3.1 Do star clusters form in virial equilibrium?

Probably the most popular model of star formation at the moment is that of 'star formation in a crossing time' (Elmegreen 2000; see also many articles in 'Protostars and Planets V'). In this scenario star formation is violent and short-lived, and the GMCs from which stars form are highly turbulent, and possibly globally unbound, structures. Stars form in dense knots and filaments created by the turbulent structure of the gas (see e.g. Padoan & Nordlund 2002,2004; Klessen & Burkert 2000; Klessen 2001; Li et al. 2003; Jappsen et al. 2005).

In such a scenario there is no reason to expect stars to form in virial equilibrium. It is plausible to imagine situations where the stellar content is hot (e.g. different star forming knots form in regions with large relative velocities), or cold (e.g. despite the supersonic velocities of much of the gas, stars form in almost stationary converging flows). Indeed, depending on the details of the turbulence in any one GMC it is quite reasonable to think that either possibility may occur. It is also reasonable to imagine a situation where the initial

virial equilibrium depends on the true SFE (e.g. higher SFEs imply more dense converging regions with high or low relative velocity dispersions). Without a fuller understanding of GMC formation and subsequent star formation it is quite impossible to draw any reasonable conclusions about what we should expect.

Indeed, in such a scenario there is no reason to assume that the initial spacial distribution of the stars and gas should be very similar. Stars will form in dense knots which may not match the large scale mass (potential) distribution of the gas. Therefore the assumption underlying eqn. 2 that $\Omega_\star = \epsilon^2 \Omega_0$ may well be incorrect. In such a situation the problem becomes intractable and will depend on the exact details of the turbulent velocity and density structure of the GMC. However, it is still possible to connect the eSFE to the true SFE through the f-parameter, even if we have no feel for its expected value(s).

3.2 Are star clusters in virial equilibrium at the onset of gas expulsion?

The virial state of the stars at the onset of gas expulsion is the crucial parameter in determining the survivability of the cluster. After the stars have formed, and before gas expulsion begins there is a window of oppor-

tunity for a cluster to relax into virial equilibrium (e.g. Verschueren 1990).

In only a few crossing times a cluster that is far from virial equilibrium can relax to close to virial equilibrium (see fig. 2). This would suggest that clusters that last for a few crossing times before the onset of gas expulsion should be roughly in virial equilibrium. If we assume a constant cluster radius then the crossing time scales as M^{-1}. Therefore high-mass clusters are more likely to be close to $f = 1$ (ie. their eSFE is close to their true SFE) than low-mass clusters as they have more crossing times to reach virial equilibrium. This means that if clusters are generally born hot then high-mass clusters will be more likely to survive than low-mass clusters, conversely, if clusters are generally born cold then high-mass clusters will be less likely to survive.

However, there are two important considerations to add to this discussion.

Firstly, if clusters are born in a highly non-equilibrium state, with stars forming in knots and filaments in a background of a highly turbulent gas potential, then relaxation into virial equilibrium is presumably not a simple process. In particular in the background gas potential is highly variable it may strongly influence the evolution of the dynamical state of the stars.

Secondly, during relaxation into an equilibrium state, a cluster will oscillate around exact virial equilibrium before finally settling as illustrated in fig. 2 for the post-gas expulsion clusters with eSFEs of 40, 50 and 60%. In the case of the 40% eSFE cluster the size of the oscillation can be quite extreme, corresponding to an f factor of between 0.9 and 1.1. These examples are for initially hot (ie. post gas expulsion) clusters, but initially cold systems would do exactly the same thing whilst collapsing.

This raises the interesting possibility that an initially hot system could expand during the embedded phase and be caught at the start of gas expulsion in the cold phase of its relaxation and so have $f < 1$, increasing the chance that it will survive. This possibility re-emphasises the point that it is the virial state *immediately before* gas expulsion that is the critical state, not the virial state at birth.

4 The effect on infant mortality and cluster mass functions

As we have seen, even small departures from virial equilibrium at the onset of gas expulsion can cause significant changes in the eSFE when compared to the true SFE. Cold clusters with a low true SFE can survive, whilst hot clusters with a high true SFE may still be destroyed.

Kroupa & Boily (2002) suggested that the shape of cluster mass functions may change due to the different impact of gas expulsion on clusters of different masses - in particular, that high-mass clusters may loose their gas adiabatically and so be far more robust (see also Parmentier et al. 2008a,b). However, depending on the value of the f-factor, these conclusions may change. In particular, as noted above, if clusters have a constant radius, then high-mass clusters should be closer to virial equilibrium than low-mass clusters due to having had more crossing times to relax. Therefore, high-mass clusters are more likely to survive if all clusters are born hot, and less likely to survive if all clusters are born cold.

That it appears that gas expulsion is the best mechanism for converting a birth power-law cluster mass function into a bell-shaped old globular cluster mass function through the preferential destruction of low-mass clusters (see Kroupa & Boily 2002; Parmentier et al. 2008a,b) may suggest that clusters are generally born hot.

It may be that the environment plays an important role in setting the initial dynamical state of clusters and so determining their robustness to gas expulsion. Gieles et al. (2007) and de Grijs & Goodwin (2008) find very little evidence for infant mortality in the SMC (but see Chandar et al. 2006 for a contrary view), and Goodwin et al. (in prep) find similar low-levels of infant mortality in the LMC. This is in sharp contrast to the high-levels of infant mortality seen in the Solar Neighbourhood (Lada & Lada 2003), or in the Antennae (e.g. Whitmore et al. 2007 and references therein) or M51 (e.g. Bastian et al. 2005). Could this be due to different initial dynamical states of clusters in different galaxies?

Interestingly, the mass regimes probed in different studies are very different. High-levels of infant mortality are seen for low-mass clusters locally, and high-mass clusters in the Antennae and M51. However, the low-levels of infant mortality are seen for intermediate-mass clusters in the SMC and LMC. If cluster formation is universal, then this may suggest that low- and high-mass clusters are hot, whilst intermediate-mass clusters are cold.

However, we have no information about the mortality rates of intermediate- and high-mass clusters locally, low- or high-mass clusters in the SMC and LMC, or low- and intermediate-mass clusters in the Antennae or M51. Therefore it is impossible to distinguish any possible variation in initial dynamical states with host galaxy or cluster mass.
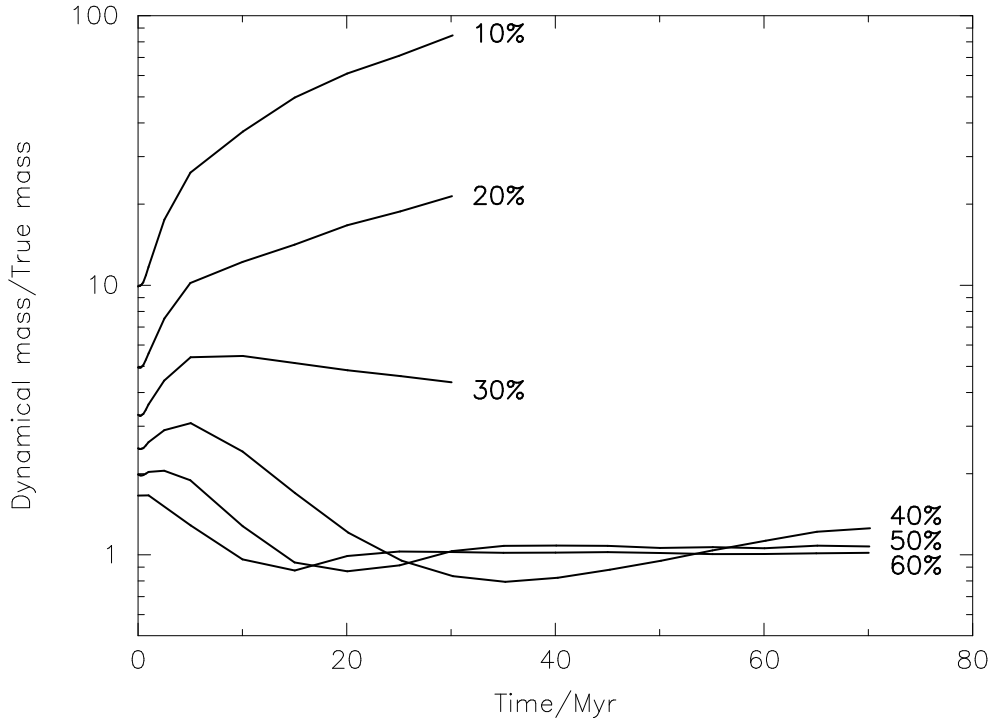
Fig. 2 The ratio of the dynamical mass to the true mass of a star cluster with time after gas expulsion for clusters with initial virial ratios $1/2\epsilon$, where ϵ corresponds to an SFE of $10, 20, 30, 40, 50$ and 60%. The difference between the dynamical and true masses is due to the stars being out of virial equilibrium. Note that for $\epsilon = 0.4 - 0.6$ (some of) the clusters re-virialise, but oscillate around a virial ratio of 0.5. From Goodwin & Bastian (2006)

5 Conclusions

The crucial factor in determining if a cluster will survive gas expulsion is the virial state of the stars immediately before the conset of gas expulsion. If the stellar component of clusters is born dynamically 'cold', then clusters are far more likely to survive the destructive effects of gas expulsion.

It is currently unclear what the initial or pre-gas expulsion dynamical states of stars in clusters is. It may be that the dynamical state depends on the cluster mass, or on the environment in a complex way.

References

Baumgardt, H. & Kroupa, P. 2007, MNRAS, 380, 1589

Bastian, N., Gieles, M., Lamers, H. J. G. L. M., Scheepmaker, R. A. & de Grijs, R. 2005, A&A, 431, 905

Bastian, N. & Goodwin, S. P. 2006, MNRAS, 369, L9

Boily, C. M. & Kroupa, P. 2003a, MNRAS, 338, 643

Boily, C. M. & Kroupa, P. 2003a, MNRAS, 338, 673

Chandar, R., Fall S. M. & Whitmore, B. C. 2006, ApJ, 650, L111

Elmegreen, B. G. 1983, MNRAS, 203, 1011

Elmegreen, B. G. & Clemens, C. 1985, ApJ, 294, 523

Elmegreen, B. G. 2000, ApJ, 530, 277

de Grijs, R. & Goodwin, S. P. 2008, MNRAS, in press

Gieles, M., Lamers, H. J. G. L. M., Portegies Zwart, S. F. 2007, ApJ, 668, 268

Goodwin, S. P. 1997a, MNRAS, 284, 785

Goodwin, S. P. 1997b, MNRAS, 286, 669

Goodwin, S. P. & Bastian, N. 2006, MNRAS, 373, 752

Gyer, M. P. & Burkert, A. 2001, MNRAS, 323, 988

Hills, J. G. 1980, ApJ, 235, 986

Jappsen, A.-K., Klessen, R. S., Larson, R. B., Li, Y. & Mac Low M.-M. 2005, A&A, 435, 611

Klessen, R. S. & Burkert, A. 2000, ApJS, 128, 287

Klessen, R. S. 2001, ApJ, 556, 837

Kroupa, P. & Boily, C. M. 2002, MNRAS. 336, 1188

Lada, C. J., Margulis, M. & Dearborn, D. 1984, ApJ, 285, 141

Lada, C. J. & Lada E. A. 2003, ARAA, 41, 57

Li, Y., Klessen, R. S. & Mac Low, M.-M. 2003, ApJ, 592, 975

Mathieu, R. D. 1983, ApJ, 267, 97

Padoan, P. & Nordlund, Å 2002, ApJ, 576, 870

Padoan, P. & Nordlund, Å 2004, ApJ, 617, 559

Parmentier, G., Baumgardt, H. & Kroupa P. 2008a, MNRAS, in press

Parmentier, G., Goodwin, S. P., Kroupa, P. & Baumgardt, H. 2008b, ApJ, submitted

Pinto, F. 1987, PASP, 99, 1161

Verschueren, W. & David, M. 1989, A&A, 219, 105

Verschueren, W. 1990, A&A, 234, 156

Whitmore, B. C., Chandar, R., & Fall, S. M. 2007, AJ, 133, 1067