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Evidence for the Strong Effect of Gas Removal on the Internal Dynamics of Young Stellar Clusters

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ABSTRACT

We present detailed luminosity profiles of the young massive clusters M82-F, NGC 1569-A, and NGC 1705-1 which show significant departures from equilibrium (King and EFF) profiles. We compare these profiles with those from N-body simulations of clusters which have undergone the rapid removal of a significant fraction of their mass due to gas expulsion. We show that the observations and simulations agree very well with each other suggesting that these young clusters are undergoing violent relaxation and are also losing a significant fraction of their *stellar* mass.

That these clusters are not in equilibrium can explain the discrepant mass-to-light ratios observed in many young clusters with respect to simple stellar population models without resorting to non-standard initial stellar mass functions as claimed for M82-F and NGC 1705-1. We also discuss the effect of rapid gas removal on the complete disruption of a large fraction of young massive clusters (“infant mortality”). Finally we note that even bound clusters may lose > 50% of their initial *stellar* mass due to rapid gas loss (“infant weight-loss”).

Key words: galaxies: star clusters – stellar dynamics – methods: N-body simulations

1 INTRODUCTION

It is thought that the vast majority of stars are formed in star clusters (Lada & Lada 2003). During the collapse and fragmentation of a giant molecular cloud into a star cluster, only a modest percentage ($\sim 30-60$ %) of the gas is turned into stars (e.g. Lada & Lada 2003). Thus, during the initial phases of its lifetime, a star cluster will be made up of a combination of gas and stars. However, at the onset of stellar winds and after the first supernovae explosions, enough energy is injected into the gas within the embedded cluster to remove the gas on timescales shorter than a crossing time (e.g. Hills 1980; Lada et al. 1984; Goodwin 1997a). The resulting cluster, now devoid of gas, is far out of equilibrium, due to the rapid change in gravitational potential energy caused by the loss of a significant fraction of its mass.

While this process is fairly well understood theoretically (e.g. Hills 1980; Mathieu 1983; Goodwin 1997a,b; Boily & Kroupa 2003a,b), its effects have received little consideration in observational studies of young massive star clusters.

In particular, many studies have recently attempted to constrain the initial stellar mass function (IMF)[1] in clusters by studying the internal dynamics of young clusters. By measuring the velocity dispersion and half-mass radius of a cluster, and assuming that the cluster is in Virial equilibrium, an estimate of the dynamical mass can be made. By then comparing the ratio of dynamical mass to observed light of a cluster to simple stellar population models (which require an input IMF) one can constrain the slope or lower/upper mass cuts of the IMF required to reproduce the observations. Studies which have done such analyses have found discrepant results, with some reporting non-standard IMFs (e.g. Smith & Gallagher 2001, Mengel et al. 2002) and others reporting standard Kroupa (2002) or Salpeter (1955) type IMFs (e.g. Maraston et al. 2004; Larsen & Richtler 2004).

However, Bastian et al. (2006) noted an age-dependence in how well clusters fit standard IMFs, in the sense that all clusters >100 Myr were well fit by Kroupa or Salpeter IMFs, while the youngest clusters showed a significant scatter. They suggest that this is due to the youngest (tens of Myr) clusters being out of equilibrium, hence undercutting the underlying assumption of Virial equilibrium needed for such studies.

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[1] We note that estimates based on dynamical masses are in fact sensitive to the present mass function (MF). However, it is assumed that for the young clusters studied the MF is likely to be a good representation of the *initial* mass function (IMF).

In order to test this scenario, in the present work we shall look at the detailed luminosity profiles of three young massive clusters, namely M82-F, NGC 1569-A, & NGC 1705-1, all of which reside in nearby starburst galaxies. M82-F and NGC 1705-1 have been reported to have non-standard stellar IMFs (Smith & Gallagher 2001, McCrady et al. 2005, Sternberg 1998). Here we provide evidence that they are likely not in dynamical equilibrium due to rapid gas loss, thus calling into question claims of a varying stellar IMF. NGC 1569-A appears to have a standard IMF (Smith & Gallagher 2001) based on dynamical measurements, however we show that this cluster is likely also out of equilibrium. Throughout this work we adopt ages of M82-F, NGC 1569-A, and NGC 1705 to be 60 ± 20 Myr (Gallagher & Smith 1999), 12 ± 8 Myr (Anders et al. 2004) and 10–20 Myr (Heckman & Leitherer 1997) respectively.

Studies of star clusters in the Galaxy (e.g. Lada & Lada 2003) as well as extragalactic clusters (Bastian et al. 2005a, Fall et al. 2005) have shown the existence of a large population of young ($<$ 10-20 Myr) short-lived clusters. The relative numbers of young and old clusters can only be reconciled if many young clusters are destroyed in what has been dubbed “infant-mortality”. It has been suggested that rapid gas expulsion from young cluster which leaves the cluster severely out of equilibrium would cause such an effect (Bastian et al. 2005a). We provide additional evidence for this hypothesis in the present work.

The paper is structured in the following way. In § 2 and § 3 we present the observations (i.e. luminosity profiles) and models of early cluster evolution, respectively. In § 4 we compare the observed profiles with our N-body simulations and in § 5 we discuss the implications with respect to the dynamical state and the longevity of young clusters.

2 OBSERVATIONS

For the present work, we concentrate on *F555W* (V) band observations of M82-F, NGC 1569-A, and NGC 1705-1 taken with the *High-Resolution Channel* (HRC) of the *Advanced Camera for Surveys* (ACS) on-board the *Hubble Space Telescope* (HST). The ACS-HRC has a plate scale of 0.027 arcseconds per pixel. All observations were taken from the HST archive fully reduced by the standard automatic pipeline (bias correction, flat-field, and dark subtracted) and drizzled (using the MultiDrizzle package - Koekemoer et al. 2002) to correct for geometric distortions, remove cosmic rays, and mask bad pixels. The observations of M82-F are presented in more detail in McCrady et al. (2005). Total exposures were 400s, 130s, and 140s for M82-F, NGC 1569-A, and NGC 1705-1 respectively.

2.1 Cluster profiles

Due to the high signal-to-noise of the data, we were able to produce surface brightness profiles for each of the three clusters on a per-pixel basis. The flux per pixel was background subtracted and transformed to surface brightness. The inherent benefit of using this technique, rather than circular apertures, is that it does not assume that the cluster is circularly symmetric. This is particularly important for M82-F, which is highly elliptical (e.g. McCrady et al. 2005). For M82-F we took a cut through the major axis of the cluster. The results are shown in the top panel of Fig. 1. We note that a cut along the minor-axis of this cluster as well as using different filters (U, B, and I - also from *HST-ACS/HRC* imaging) would not change the conclusions presented in § 4 & § 5.

For NGC 1569-A and NGC 1705-1 we were able to assume circular symmetry (after checking the validity of this assumption) and hence we binned the data as a function of radius from the centre. The results for these clusters are shown in the centre and bottom panels of Fig. 1, where the circular data points represent mean binning in flux and the triangles represent median binning. The standard deviation of the binned (mean) data points is shown. We also note that our conclusions would remain unchanged (§ 4 & § 5) if we used the *F814W* (I) *HST-ACS/HRC* observations.

We did not correct the surface brightness profiles for the PSF as the effects that we are interested in happen far from the centre of the clusters and therefore should not be influenced by the PSF. In all panels of Fig. 1 we show the PSF as a solid green line (taken from an *ACS-HRC* observation of a star in a non-crowded region). The background of the area surrounding each cluster is shown by a horizontal dashed line.

In order to quantify our results, we fit two analytical profiles to the observed LPs. The first is a King (1962) function, which fits well the Galactic globular clusters and is characterised by centrally concentrated profiles with distinct tidal cut-offs in their outer regions. The second analytical profile used is an Elson, Fall, & Freeman (EFF - 1987) profile, which is also centrally concentrated with a non-truncated power-law envelope. The EFF profile has been shown to fit young clusters in the LMC better (EFF) as well as young massive clusters in galaxies outside the local group (e.g. Larsen 2004; Schweizer 2004). The best fitting King and EFF profiles are shown as blue/dashed and red/solid lines respectively. The fits were carried out on all points within 0.5” of the centre of the clusters, i.e. the point at which, from visual inspection, the profile deviates from a smoothly decreasing function.

As is evident in Fig. 1 all cluster profiles are well fit by both King and EFF profiles in their inner regions. *However, none of the clusters appear tidally truncated, in fact all three clusters display an excess of light at large radii with respect to the best fitting power-law profile.* The points of deviation from the best fitting EFF profiles are marked with arrows. This result will be further discussed in § 4.

Due to the rather large distance of the galaxies as well as the non-uniform background around the clusters presented here, background subtraction is non-trivial. However, we have checked the effect of selecting different regions surrounding the clusters and note that our conclusions remain unchanged. We also note that in the LMC, where the background can be much more reliably determined, many clusters show excess light at large radii (e.g. EFF; Elson 1991; & Mackey & Gilmore 2003).

3 SIMULATIONS

We model star clusters using N-body simulations. Star clusters are constructed as Plummer (1911) spheres using the

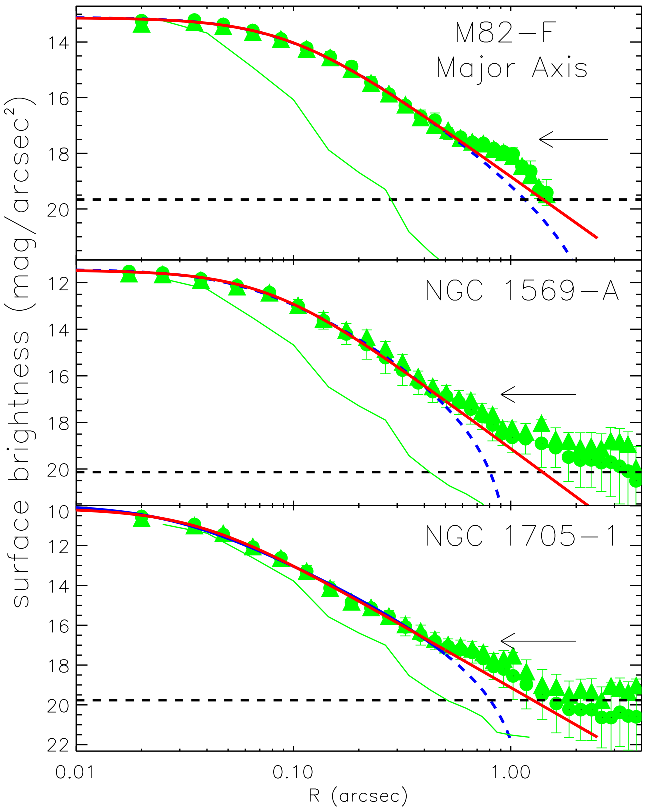

Figure 1. The luminosity profile of the young massive clusters M82-F, NGC 1569-A, NGC 1705-1. The data are shown as filled green symbols, where the circles are the mean of the flux at that radius and the triangles are the median of the flux. Error bars represent the standard deviation of pixels in that annulus (based on the mean flux). The PSF is shown as a solid green line and the background value is the horizontal dashed line. The best fitting King (blue/dashed) and EFF (red/solid) profiles are shown, see text. The fits were carried out for $R < 0.5''$. Note that all clusters contain excess light at large radii relative to either of the profiles, the break from the EFF profile is noted by an arrow.

prescription of Aarseth et al. (1974) which require the Plummer radius R_P and total mass M_P to be specified. Clusters initially contain 30000 equal-mass stars[2]. Simulations were conducted on a GRAPE-5A special purpose computer at the University of Cardiff using a basic N-body integrator (the speed of the GRAPE hardware means that sophisticated codes are not required for a simple problem such as this).

The expulsion of residual gas from star clusters has been modelled by several authors (see in particular Lada et al. 1984; Goodwin 1997a,b; Geyer & Burkert 2001; Kroupa et al. 2001; Boily & Kroupa 2003a,b). The typical method is to represent the gas as an external potential which is removed on a certain timescale. Gas removal is expected to be effectively instantaneous, i.e. to occur in less than a crossing time (e.g. Goodwin 1997a; Melioli & de Gouveia dal Pino 2006). As such we require no gas potential, and can model the cluster as a system that is initially out of Virial equilibrium (equivalent to starting the simulations at the end of the gas expulsion). The subsequent evolution is the violent relaxation (Lynden-Bell 1967) of the cluster as it attempts to return to Virial equilibrium.

We define an *effective* star formation efficiency ϵ which parameterises how far out of Virial equilibrium the cluster is after gas expulsion. A cluster which initially contains 50 % stars and 50 % gas (i.e. a 50 % star formation efficiency) which is initially in Virial equilibrium will have a stellar velocity dispersion that is a factor of $\sqrt{2}$ - more generally $\sqrt{1/\epsilon}$ - too large to be virialised after the gas is (instantaneously) lost. We define the efficiency as effective, as it assumes that the gas and stars are initially in Virial equilibrium, which may not be true.

We choose as initial conditions, $R_P = 3.5$ pc (corresponding to a half mass radius of ~ 4 pc) and $M_P/\epsilon = 5 \times 10^4$ or $7.5 \times 10^4 M_\odot$ (i.e. the total initial stellar plus gas mass was 5×10^4 or $7.5 \times 10^4 M_\odot$) as representative of young massive star clusters. In order to compare the simulations with our observations we place the simulations at our assumed distance of M82, namely 3.6 Mpc (assuming that it is at the same distance as M81 - Freedman et al. 1994).

4 A COMPARISON OF SIMULATIONS AND OBSERVATIONS

Previous simulations have shown that for $\epsilon < 0.3$ clusters are totally destroyed by gas expulsion, but for higher ϵ significant (stellar) mass loss occurs, but a bound core remains (Goodwin 1997a,b; Boily & Kroupa 2003a,b). For $\epsilon = 0.4, 0.5$ and 0.6 respectively, $\sim 65, 35$ and 15 % of the initial stellar mass is lost within ~ 30 Myr. We confirm those results.

The escaping stars are not lost instantaneously, however. Stars escape with a velocity of order of the initial velocity dispersion of the cluster, typically a few km s^{-1}. Therefore, escaping stars will still be physically associated with the cluster for 10 – 40 Myr *after* gas expulsion. These stars produce a 'tail' in the surface brightness profile and produce the observed excess light at large radii.

We assume a constant mass-to-light ratio for the simulation and convert the projected mass density into a luminosity and hence surface brightness profile. The normalisation of the surface brightness is arbitrary and scaled so that the central surface brightness is similar to that of the observed clusters.

Two of the simulations are shown in Fig. 2. The filled circles are the surface brightness of the simulated cluster, with the specific parameters (total initial mass, ϵ, and time since gas expulsion) of the simulations shown. We follow the same fitting technique as with the observations, namely fitting King and EFF profiles (dashed blue and solid red lines respectively) to the profile. As was seen in the observations, the simulations display excess light at large radii.

The detailed correspondence between the observations and simulations presented here lead us to conclude that M82-F, NGC 1569-A and NGC 1705-1 display the signature of rapid gas removal and hence are *not in dynamical equilibrium.* In future works we will provide a large sample of luminosity profiles of young massive extragalactic star clus-

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[2] Tests show that the results do not depend on N, or the gravitational softening. This is because the dynamics we model are those of violent relaxation to a new potential and so 2-body encounters are unimportant.

ters, as well as a detailed set of models which can be used to constrain the star formation efficiency of the clusters. Here we simply note that models with a SFE between 40-50% best reproduce the observations.

Similar surface brightness profiles with an excess of light at large radii are seen in young LMC clusters: see EFF and Elson (1991) in which many clusters clearly show these unusual profiles, and also Mackey & Gilmore (2003) - in particular for R136. These profiles are also well matched by our simulations. McLaughlin & van der Marel (2005) have compiled a data base of structural parameters for young LMC/SMC clusters and compare the M/L ratio from dynamical estimates to that predicted by simple stellar population models (i.e. to check the dynamical state of the young clusters). However, the study was limited as the young clusters tend to be of relatively low-mass, making it difficult to measure accurate velocity dispersions. Here we simply note that the five clusters in their sample younger than 100 Myr all show significant deviations in the M/L ratio, but also note that this may simply be due to stochastic measurement errors.

5 IMPLICATIONS AND CONCLUSIONS

It appears likely that the excess light at large radii seen in many massive young star clusters is a signature of violent relaxation after gas expulsion. This suggests that these clusters have effective star formation efficiencies of around 40 – 50 %, such that they show a significant effect, but do not destroy themselves rapidly.

5.1 Virial equilibrium of young star clusters

It should also be noted that the escaping stars are not just physically associated with a cluster in the surface brightness profiles. Measurements of the velocity dispersion of the cluster will also include the escaping stars. This will result in an artificially high velocity dispersion that reflects the initial total stellar *and* gaseous mass. Thus, mass estimates based on the assumption of stellar Virial equilibrium may be wrong by a factor of up to three for 10–20 Myr after gas expulsion as is shown in Fig. 3 for $\epsilon = 40,\ 50$ and 60 % clusters (i.e. at the ages of NGC 1569-A and NGC 1705-1).

Clusters with $\epsilon \sim 50$ –60 % rapidly readjust to their new potential and the virial mass estimates become fairly accurate 10 – 15 Myr after gas expulsion (i.e. for a cluster age of 15 – 20 Myr). However, for $\epsilon \sim 40$ %, the virial mass is significantly greater than the actual mass for ~ 10 Myr and clusters do not settle into virial equilibrium for ~ 50 Myr Indeed, between 30 and 40 Myr after gas expulsion the virial mass estimate *underestimates* the total mass by up-to 30 % as the cluster has over-expanded.

A few recent studies have reported non-Kroupa (2002) or non-Salpeter (1955) type initial stellar mass functions (IMF) in young star clusters (e.g. Smith & Gallagher 2001; Mengel et al. 2002). These results were based on comparing dynamical mass estimates (found by measuring the velocity dispersion and half-mass radius of a cluster and assuming Virial equilibrium) and the light observed from the cluster with simple stellar population models (which assume an input stellar IMF). Other studies based on the same technique (e.g. Larsen & Ritchler 2004; Maraston et al. 2004) have reported standard Kroupa- or Salpeter-type IMFs.

Recently, Bastian et al. (2006) noted a strong age dependence on how well young clusters fit SSP models with standard IMFs, with all clusters older than ~ 100 Myr being will fit by a Kroupa IMF. Based on this age dependence, they suggested that the youngest star clusters (< 80 Myr) may not be in Virial equilibrium. The observations presented here strongly support this interpretation as M82-F and NGC 1705-1 both seem to have been strongly affected by rapid gas loss. While NGC 1569-A has been reported to have a Salpeter-type IMF (Smith & Gallagher 2001), the excess light at large radii suggests that this cluster has also undergone a period of violent relaxation and stars lost during this are still associated with the cluster even though its velocity dispersion correctly measures its mass..

It should be noted that the obvious signature of violent relaxation in the profile of M82-F suggests that it is at the lower end of its age estimate of 60 ± 20 Myr (Gallagher & Smith 1999), as by $40 - 50$ Myr the tail of stars becomes disassociated from the cluster. Another possibility is that M82-F has been tidally shocked and has had a significant amount of energy input into the cluster, thus mimicking the effects of gas expulsion. Whichever is the case, the tail of stars from M82-F - whatever its age - is a signature of violent relaxation and strongly suggests that it is out of virial equilibrium.

5.2 Infant Mortality

If a young star cluster has a low enough effective star formation efficiency (< 30 %) it can become completely unbound and dissolve over the course of a few tens of Myr. This mechanism has been invoked to explain the expanding OB associations in the Galaxy (Hills 1980). Recent studies of large extragalactic cluster populations in M 51 (Bastian et al. 2005a) and NGC 4038/39 (Fall et al. 2005) have shown a large excess of young (<10 Myr) clusters relative to what would be expected for a continuous cluster formation history. Both of these studies suggest that the excess of extremely young clusters is due to a population of short-lived unbound clusters. The rapid dissolution of these clusters has been dubbed “infant mortality”.

The observations and simulations presented here support such a scenario. If the star formation efficiency is less than 30% - no matter what the mass - the rapid removal of gas completely disrupts a cluster (although see Fellhauer & Kroupa 2005 for a mechanism which can produce a bound cluster with $\epsilon \sim 20\%$). Even if ϵ is large enough to leave a bound cluster, the cluster may be out of equilibrium enough for external effects to completely dissolve it, such as the passage of giant molecular clouds (Gieles et al. 2006) or in the case of large cluster complexes, other young star clusters.

Interestingly, gas expulsion often significantly lowers the *stellar* mass of the cluster even if a bound core remains (see § 3). Thus, relating the observed mass function of clusters to the birth mass function needs to account not only for infant mortality, but also for ‘infant weight-loss’ in which a cluster could lose > 50 % of its initial *stellar* mass in < 50 Myr.

The current simulations do not include either a stellar IMF, nor the evolution of stars. The inclusion of these effects do not significantly effect the results as the mass-loss due to stellar evolution is low compared to that due to gas expulsion (see Goodwin 1997a,b). In particular, we do not expect the preferential loss of low-mass stars as these clusters are too young for equipartition to have occured, thus stars of all masses are expected to have similar velocities. One caveat to this is the effect of primordial mass (hence velocity) segregation which may mean that the most massive stars are very unlikely to be lost as they have the lowest velocity dispersion. We will consider such points in more detail in a future paper.

6 SUMMARY

Observations of the surface brightness profiles of the massive young clusters M82-F, NGC 1569-A, and NGC 1705-1 show a significant excess of light at large radii compared to King or EFF profiles. Simulations of the effects of gas expulsion on massive young clusters produce exactly the same excess due to stars escaping during a period of violent relaxation. Gas expulsion can also cause virial mass estimates to be significantly wrong for several 10s of Myr.

These signatures are also seen in many other young star clusters (e.g. Elson 1991; Mackey & Gilmore 2003) and suggest that gas expulsion is an important phase in the evolution of young clusters that cannot be ignored. In particular, this shows that claims of unusual IMFs for young star clusters are probably in error as these clusters are *not* in virial equilibrium as is assumed.

In future work we will further explore the dynamical state of young clusters in order to constrain the star-formation efficiency within the clusters.

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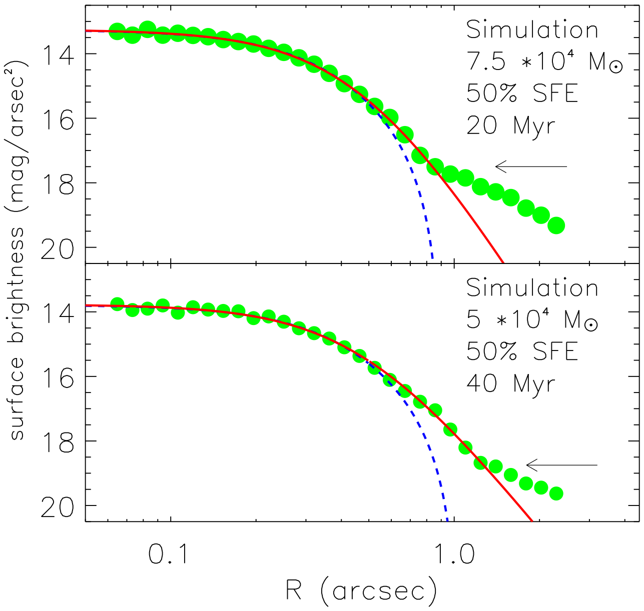

Figure 2. Two simulations of the effect of rapid gas loss on a young star cluster. The green filled circles are the simulations, with a vertical scaling to match the observed clusters (see text). We have transformed the simulations from parsecs to arcseconds assuming a distance to the clusters of 3.6 Mpc. The details of each simulation are shown in the respective panels. The blue/dashed and red/solid lines are the best fitting King and EFF profiles, respectively. The fits were carried out for $R \leqslant 0.5$. Note the large excess of the light at large radii with respect to the EFF profile. The point of departure of the surface brightness profile from the EFF profile is noted by an arrow.

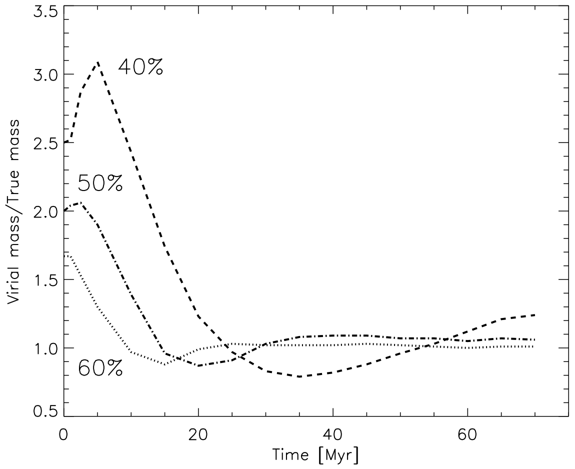

Figure 3. The variation of the virial-mass-to-true-mass ratio with time for effective star formation efficiencies of 40, 50 and 60 %. The virial mass is measured from the velocity dispersion of stars within 20 pc of the cluster centre and the true mass is the total mass of stars within 20 pc of the cluster. Note that zero time is the time of gas expulsion, and so the cluster age is ~ 5 Myr greater than this time.

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