On the infant weight loss of low- to intermediate-mass star clusters

C. Weidner,1⋆ P. Kroupa,2⋆ D. E. A. Nünberger3⋆ and M. F. Sterzik3⋆

1Departamento de Astronomía y Astrofísica, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Macul, Santiago, Chile
2Argelander-Institut für Astronomie (Sternwarte), Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany
3European Southern Observatory, Alonso de Córdova 3107, Santiago, Chile

Accepted 2007 January 30. Received 2007 January 22; in original form 2006 November 3

ABSTRACT

Star clusters are born in a highly compact configuration, typically with radii of less than about 1 pc roughly independently of mass. Since the star formation efficiency is less than 50 per cent by observation and because the residual gas is removed from the embedded cluster, the cluster must expand. In the process of doing so it only retains a fraction \( f_{st} \) of its stars. To date there are no observational constraints for \( f_{st} \), although \( N \)-body calculations by Kroupa, Aarseth & Hurley suggest it to be about 20–30 per cent for Orion-type clusters. Here we use the data compiled by Testi et al., Testi, Pall & Natta and Testi, Pall & Natta for clusters around young Ae/Be stars and by de Wit et al. and de Wit et al. around young O stars and the study of de Zeeuw et al. of OB associations and combine these measurements with the expected number of stars in clusters with primary Ae/Be and O stars, respectively, using the empirical correlation between maximal stellar mass and star cluster mass of Weidner & Kroupa. We find that \( f_{st} < 50 \) per cent with a decrease to higher cluster masses/more massive primaries. The interpretation would be that cluster formation is very disruptive. It appears that clusters with a birth stellar mass in the range \( 10^2 \)–\( 10^5 \) \( M_\odot \) keep at most 50 per cent of their stars.

Key words: stellar dynamics – stars: early-type – stars: formation – Galaxy: formation – open clusters and associations: general.

1 INTRODUCTION

The birth sites of star clusters are dense molecular clouds. As the star formation efficiency, \( \epsilon = \frac{M_{st}}{(M_{st} + M_{gas})} \), where \( M_{st} \) and \( M_{gas} \) is the mass in stars and gas, respectively, just before star formation ceases, is generally believed to be low, the expulsion of the surrounding gas leads to the release of a large fraction of the stars from the clusters.

The most-efficient mechanisms for gas expulsion are the radiation and winds of massive stars and supernovae. Kroupa (2005) gives a simple example which shows that the luminosity output of the OB stars should be strong enough to destroy their natal cloud, as, for example, a 15-\( M_\odot \) star releases as much as \( 3 \times 10^{50} \) erg per 0.1 Myr into its surrounding medium while a cluster of \( 10^4 \) \( M_\odot \) has only a binding energy of \( 8.6 \times 10^{48} \) erg. Therefore, the cloud should be dispersed, even before the occurrence of the first supernova. An observational example is the Orion Nebula cluster which is practically gas-free in its centre despite its young age of about 1 Myr (Hillenbrand & Hartmann 1998). However, strong ‘luminosity leakages’ through low-density holes in the molecular clouds may dampen the effect of radiation arising from OB stars (Dale et al. 2005). In this case, supernovae may play significant a role in dissolving molecular clouds (Wheeler & Bash 1977; Goodwin 1997).

Rapid removal of gas in the case of \( \epsilon < 0.5 \) probably leads to the total destruction of the clusters (Tutukov 1978; Hills 1980; Mathieu 1983; Lada, Margulis & Dearborn 1984). Observations show that \( \epsilon \approx 0.2–0.4 \) (Nünberger et al. 2002; Lada & Lada 2003) but bound star clusters like the Pleiades and the Hyades do exist. The problem of cluster survival after gas expulsion has been identified as one of the key problems in astrophysical research (Davies et al. 2006).

With the use of the Aarseth (1999) NBODY6 algorithm and including 100 per cent primordial binaries, stellar evolution and a realistic Galactic tidal field, Kroupa et al. (2001) re-examined the problem of cluster survival after gas expulsion. They showed that from an embedded cluster with \( 10^4 \) stars and brown dwarfs, a bound object with about 25 per cent of the initial number of stars can survive, even with \( \epsilon = 0.33 \) and explosive residual-gas removal. This remnant cluster is the core of an expanding OB association. Thus, the Pleiades and Hyades may have formed from a compact Orion Nebula type object but only retained \( f_{st} \approx 0.25 \) of their birth stellar mass after removal of their residual gas. This fraction, however, depends on the radial density profile of the pre-expulsion cluster (Boily & Kroupa 2003a,b), and also on the relative distribution of the stars and gas (Adams 2000).

Kroupa & Boily (2002) studied the effect of cluster dissolution on the observed initial cluster mass function (ICMF). They concluded...
that three different regimes of clusters may exist which they call type I, II and III clusters.

(i) Type I. Sparse low-mass clusters which contain no O stars. They have stellar masses, \( M_{\text{cl}} \), below \( 300 M_\odot \) or \( N_{\text{cl}} < 1000 \) stars. As the stellar winds and ionizing radiation of the stars is low because of the lack of O stars, the gas expulsion time-scale is of the same order as the crossing time of the cluster (a few Myr). Thus, Kroupa & Boily (2002) expected \( f_{\text{st}} \approx 0.5 \) for type I clusters.

(ii) Type II. Clusters with \( 10^3 \lesssim N_{\text{cl}} \lesssim 10^5 \) or \( 300 \lesssim M_{\text{cl}} \lesssim 30000 M_\odot \). They have only a few O stars. However, due to their still rather low-mass, gas expulsion is 'explosive' on a time-scale of a few \( 10^7 \) yr. Given the destructive residual-gas expulsion Kroupa & Boily (2002), suggested \( f_{\text{st}} \approx 0.1-0.2 \) for type II clusters.

(iii) Type III. Massive clusters with more than \( N_{\text{cl}} \gtrsim 10^5 \), \( M_{\text{cl}} \gtrsim 30000 M_\odot \). These clusters can have thousands of O stars but due to the high mass the ionized gas is expelled adiabatically, with a time-scale longer than the crossing-time of the cluster. If this is correct, then \( f_{\text{st}} \approx 0.5 \) for type III clusters.

The problem Kroupa & Boily (2002) faced was that \( f_{\text{st}} \) was virtually unconstrained by observations.

The aim of this contribution is to show how the fraction of retained stars for type I and low-mass type II clusters may be observationally constrained in order to improve our understanding of their very early evolution and possible fate. To achieve this a large set of observations addressing the issue of clustering around young intermediate-mass stars available in the literature (Testi et al. 1997, 1998, 1999; de Zeeuw et al. 1999; de Wit et al. 2004, 2005) is used.

In Section 2 we describe the procedure to calculate the surviving star fraction. This is followed by Section 3 where the results of this work are presented before they are discussed in Section 4.

2 THE PROCEDURE

2.1 The stellar initial mass function

The following multicomponent power-law initial mass function (IMF) is used to estimate the number of stars expected in a star cluster:

\[
\xi(m) = k \begin{cases} 
\left( \frac{m}{m_{\text{min}}} \right)^{-\alpha_0}, & m_{\text{low}} \leq m < m_{\text{H}}, \\
\left( \frac{m}{m_{\text{H}}} \right)^{-\alpha_1}, & m_{\text{H}} \leq m < m_{\text{O}}, \\
\left( \frac{m}{m_{\text{O}}} \right)^{-\alpha_2}, & m_{\text{O}} \leq m < m_{1}, \\
\left( \frac{m}{m_{1}} \right)^{-\alpha_3}, & m_{1} \leq m < m_{\text{max}},
\end{cases}
\]

with exponents

\[
\alpha_0 = +0.30, \quad 0.01 \leq m/M_\odot < 0.08, \\
\alpha_1 = +1.30, \quad 0.08 \leq m/M_\odot < 0.50, \\
\alpha_2 = +2.35, \quad 0.50 \leq m/M_\odot < 1.00, \\
\alpha_3 = +2.35, \quad 1.00 \leq m/M_\odot.
\]

where \( dN = \xi(m) \, dm \) is the number of stars in the mass interval \( m \) to \( m + \, dm \). The exponents \( \alpha_i \) represent the standard or canonical IMF (Kroupa 2001, 2002). The advantage of such a multipart power law description are the easy integrability and, more importantly, that different parts of the IMF can be changed independently without affecting other parts. Note that this form is a two-part power law in the stellar regime, and that brown dwarfs contribute about 4 per cent by mass only. A lognormal form below 1 M_\odot with a power-law extension to high masses was suggested by Chabrier (2003). Today the observed IMF is understood to be an invariant Salpeter/Massey power-law slope (Salpeter 1955; Massey 2003) above 1 M_\odot, being independent of the cluster density and metallicity for metallicities \( Z \gtrsim 0.002 \) (Massey & Hunter 1998; Massey 1998, 2002, 2003; Sirianni et al. 2000, 2002; Parker et al. 2001; Wyse et al. 2002; Bell et al. 2003; Piskunov et al. 2004; Pflamm-Altenburg & Kroupa 2006).

The basic assumption underlying our approach is the notion that all stars in every cluster follow this same universal IMF, which is consistent with observational evidence (Elmegreen 1999; Kroupa 2001).

2.2 The maximum star mass versus cluster mass relation

In a series of recent publications (Kroupa & Weidner 2003; Weidner, Kroupa & Larsen 2004; Weidner & Kroupa 2004, 2005, 2006), the influence of stars forming predominately in star clusters which later dissolve into the field was studied. During this process support for the possibility of a maximum mass for stars was found on a statistical basis (for R136 in the Large Magellanic Cloud, Weidner & Kroupa 2004), a result later confirmed by several independent studies (Figer 2005; Oey & Clarke 2005; Koen 2006). This work then yielded to a more thorough investigation of massive stars in star clusters, resulting in the finding of a probably physical (and not statistical) relation between the mass of the most-massive star in a young (<3 Myr) star cluster and the mass of the harbouring star cluster (Weidner & Kroupa 2006). One consequence of this relation would be an ordered formation of star clusters meaning that low-mass stars form first and that star formation ceases with the appearance of the high-mass stars. This may be a natural outcome of termination of star formation by feedback, and had been suggested in the study of the Hyades and Pleiades by Herbig (1962) and in a study of NGC 3293 by Herbst & Miller (1982).

The most-massive star versus cluster mass relation (thick solid line in Fig. 1) then follows by using the cluster mass, \( M_{\text{cl}} \),

\[
M_{\text{cl}} = \int_{m_{\text{low}}}^{m_{\text{max}}} m \xi(m) \, dm
\]

and taking into account that there exists exactly one most-massive star in each cluster. This condition can be written as

\[
1 = \int_{m_{\text{max}}}^{m_{\text{max}}} \xi(m) \, dm.
\]

Here \( m_{\text{low}} = 0.01 M_\odot \) is the minimal fragmentation mass, \( m_{\text{max}} \) the most-massive star in a cluster and \( m_{\text{max}} \approx 150 M_\odot \) the measured maximal stellar mass limit (Weidner & Kroupa 2004; Figer 2005; Oey & Clarke 2005; Koen 2006). On combining equations (4) and (3) the analytical function

\[
m_{\text{max}} = m_{\text{max}}(M_{\text{cl}})
\]

is quantified by Weidner & Kroupa (2004) and shown as the thick solid line in Fig. 1.

With this relation we can now calculate the mass of the cluster for an observed most-massive (primary) star.

2.3 The data

Testi et al. (1997, 1998, 1999) study the clustering of stars around intermediate-mass pre-main-sequence stars (Herbig Ae/Be stars) with a large set of near-infrared observations with two different methods. They looked for overdensities in the photometric K-band flux around these stars in comparison to the background away from the stars and directly counted the stars found in the K band close to these stars. Some of their main results are:

Low-mass star cluster formation efficiency

This reflects the still large uncertainties in the ages and models for PMS stars.

Complementary to the Testi et al. (1998) sample, de Wit et al. (2004, 2005) searched for evidence if O stars observed in the field originate from young star-forming regions or if in situ field formation of massive stars is possible. Amongst their 43 candidate stars they found five with previously unknown small clusters surrounding them. These five stars are included in this study. The given spectral types have been converted to \( T_{\text{eff}} \) with the use of table 3 of Chlebowski & Garmany (1991). The conversion of the luminosities and \( T_{\text{eff}} \) into masses and ages is done with the same models as applied on the Testi et al. (1998) sample. Of the remaining 38 stars, de Wit et al. (2004) could trace back 27 stars to star-forming regions – making them runaway stars which were dynamically ejected from young cluster cores (Ramspeck, Heber & Moehler 2001; Pfamm-Altenburg & Kroupa 2006). The nature of the remaining 11 stars is more puzzling. de Wit et al. (2004) classify them as O stars formed in isolation, representing the lower end of the cluster mass function. However, they need a rather shallow cluster mass function with a slope of \( \beta = 1.7 \); a result in contrast to known observational values which are closer to \( \beta = 2 \) for various environments (Zhang & Fall 1999; Hunter et al. 2003; Lada & Lada 2003). Current star formation theories differ on the question if isolated formation of massive stars is possible – some argue against it (Bonnell, Bate & Zinnecker 1998; Stahler, Pallia & Ho 2000; Bonnell & Bate 2002; Bally & Zinnecker 2005), while others propagate the concept (Yorke & Sonnhalter 2002; Li, Klessen & Mac Low 2003). No unambiguous evidence for such star formation has been observationally found other than the existence of isolated O stars.

Using OB associations with known open clusters as cores is even more difficult than the above-described samples. As they grow older (>10 Myr), other dynamical effects (two-body relaxation, few-body encounters, tidal stripping due to the Galactic tidal field) already remove additional stars after all gas is lost from the remaining cluster. Furthermore, the most-massive stars may already have exploded as supernovae – making our method of estimating the cluster mass through the most-massive star impossible. Also, discrimination between members of the remaining open cluster and the OB association is difficult with current data. Additionally, an OB association can be the result of the dispersion of more than one cluster. This is actually seen, for example, in the Monoceros OB1 association which harbours the open clusters NGC 2264 and Mon R1 and in Perseus OB2 with the clusters NGC 1333 and IC 348. None the less, using the study of OB associations by de Zeeuw et al. (1999), an attempt is made to compare to the results obtained from the Testi et al. (1998) and de Wit et al. (2004) sample. Particularly suitable from that data set is the Cassiopeia–Taurus association with the open cluster \( \alpha \) Persei at its core. For Cassiopeia–Taurus 83 B stars are counted and for \( \alpha \) Persei 30 B stars. This gives a total of 113 B stars of which 27 per cent \( (f_\text{a} = 0.27) \) are retained in the cluster. An estimate of the original cluster mass is more difficult. Using an age of 50 Myr (de Zeeuw et al. 1999) for both cluster and association, the most-massive star still alive should be around 7.5 \( M_\odot \) according to the stellar evolution models described earlier in this work. The border between A and B stars is around 3.5 \( M_\odot \). Assuming a canonical IMF (see Section 2.1), 0.68 per cent of all the stars and brown dwarfs lie in the mass range between 3.5 and 7.5 \( M_\odot \). For 113 B stars this gives a total number of 16600 stars. With a mean stellar mass of 0.36 \( M_\odot \) for the canonical IMF, the resulting cluster mass is about 6000 \( M_\odot \) in stars. With the same method we analysed the association – cluster pairs Cepheus OB2 – Trumpler 37 and Monoceros OB2 – NGC 2244 from de Zeeuw et al. (1999), supplemented

![Figure 1. The logarithm of the most-massive-star versus logarithm of the stellar cluster mass. The thick solid line is the semi-analytic result from Weidner & Kroupa (2004). The thick dashed line is the result of the 'sorted sampling' Monte Carlo experiment of Weidner & Kroupa (2006). The dots with error bars are observational values for a sample of young clusters from the literature (see Weidner & Kroupa 2006, for details on the list). The large triangle is the most-massive star in a state-of-the-art hydrodynamical star cluster formation simulation (Bonnell, Bate & Vine 2003; Bonnell, Vine & Bate 2004). The thin solid line on the left-hand side of the corner, labelled with \( 'm_{\text{max}} = M_\odot' \), indicates the limit where all mass of a star cluster is concentrated only in one star.](https://academic.oup.com/mnras/article-abstract/376/4/1879/1018375)
Table 1. Number, designation, mass limits with and without extinction, $r_{\text{ecl}}$, and the observed numbers of stars ($N_{\text{obs}}$) from Testi et al. (1998) and de Wit et al. (2005). Age and mass stars derived from stellar models. $r_{\text{ecl, in}}$ and $r_{\text{ecl, now}}$ are calculated from equations (6) and (7). In the first case $N_{\text{exp,1}}$ and $r_{\text{ecl}} = 0.5$ pc is used, and in the second $N_{\text{obs}}$ and $r_{\text{ecl}}$. The initial embedded cluster masses ($M_{\text{ecl}}$) are from the maximum star mass versus cluster mass relation (Section 2.2), while the expected number of stars ($N_{\text{exp,1}}$) and the transformation factors ($f_a, 1$) for the Testi et al. (1999) and the de Wit et al. (2005) sample are derived as described in Section 2.3.

<table>
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<th>Number</th>
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<th>Limit 2 with extinction ($M_\odot$)</th>
<th>Age (Myr)</th>
<th>Mass ($M_\odot$)</th>
<th>$r_{\text{ecl, obs}}$ (pc)</th>
<th>$r_{\text{ecl, in}}$ (Myr)</th>
<th>$r_{\text{ecl, now}}$ (Myr)</th>
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</table>

<sup>a</sup>For these clusters no $r_{\text{ecl}}$ values were given in Testi et al. (1998) and de Wit et al. (2005). Therefore, the mean $r_{\text{ecl}}$ of all clusters is used.

<sup>b</sup>For these stars no mass limits were given in Testi et al. (1998).

<sup>c</sup>In Testi et al. (1998) most of the mass limits were given as <0.1 $M_\odot$. During the calculation of the expected number of stars these limits were chosen as the hydrogen burning limit of 0.08 $M_\odot$.

<sup>d</sup>For these clusters Testi et al. (1998) give only a minimum number of stars observed. Therefore, the $f_a$ values are in these cases only lower limits.

<sup>e</sup>The clusters from the de Wit et al. (2004, 2005) sample are included twice as in the paper not numbers of stars but densities of stars with large error bars are given. First they are shown with the mean $N_{\text{obs}}$ and then with the maximum $N_{\text{obs}}$.

<sup>f</sup>The $f_a$ values for these clusters in OB associations from de Zeeuw et al. (1999) are determined in a different way than the rest. See the text for details.

with data from the WEBDA<sup>1</sup> data base and from Massey, Johnson & Dégioia-Eastwood (1995). All results are shown in Table 1.

The relation between the maximum star mass and the cluster mass from Section 2.2 (equation 5) is then used to connect the masses of the most massive stars observed in the combined Testi et al. (1999) and de Wit et al. (2005) sample with the initial star cluster masses.

<sup>1</sup>http://www.univie.ac.at/webda/

With the use of the canonical IMF (equations 1 and 2) the number of stars expected for each cluster, $N_{\text{exp,2}}$, is derived for the two mass (completeness) limits, assuming 50 per cent binaries in both cases. The stars in binaries are assumed to be chosen randomly from the IMF subject to the mass-constraint imposed by our relation in Fig. 1. Table 1 shows the results of the conversion.

Also shown in Table 1 are the radii, $r_{\text{ecl}}$, of the clusters as far as they have been determined by Testi et al. (1998) or de Wit et al. (2005). In those cases where no radii were given (marked by <sup>x</sup> in Table 1) the mean of the other radii has been chosen. These radii are
needed to obtain the two-body relaxation times, $t_{rel}$, of the cluster with the use of the following formulae:

$$ t_{rel} = 0.1 \frac{N}{\ln(N)} t_{rel}^0 \text{ (Myr)} $$

and

$$ t_{rel} = \frac{2 \sigma_{rel}}{\sigma_{rel}} \approx 4 \left( \frac{100 M_\odot}{M_{ ecl}} \right)^{1/2} \left( \frac{r_{rel}}{0.5 \text{ pc}} \right)^{3/2} \text{ (Myr)}. \tag{7} $$

In Table 1, we quote the estimated initial relaxation time, assuming that the birth-cluster radii are $r = 0.5 \text{ pc}$ with $N_{\text{expl}}$ stars, and the current relaxation time, assuming the measured cluster radii and the observed number of stars. As is evident, $t_{rel,in} > \text{age}$ in the majority of the cases (66 per cent), such that the current low number of stars cannot be the result of evaporation from the cluster due to early two-body relaxation. However, $t_{rel,now} < \text{age}$ indicates that the current remnant clusters are relaxation dominated. $N$-body modelling would be required to further quantify the sum of the effect of loss of stars through gas expulsion and through the later two-body relaxation after the remnant cluster has re-virialized. However, since cluster disruption through two-body relaxation takes about $20 \times t_{rel,now}$ in a solar neighbourhood tidal field, the later relaxation-driven evaporation would not have had much time to act significantly. Stars without any evidence for clustering in the Testi et al. (1998) sample have not been included in Table 1 as they are likely dynamically ejected from their birth place (Pflamm-Altenburg & Kroupa 2006).

Several of the stars of the Testi et al. (1998) sample show considerable amounts of gas around them. All cases with an amount of gas larger than 50 per cent of the initial embedded cluster mass ($M_{ecl}$) have been excluded from further analysis and are not listed in Table 1. These clusters have not been evacuated from the gas yet and therefore have not lost stars through this process yet. Furthermore these large amounts of gas probably hide larger numbers of stars. In the remaining clusters only small quantities of gas are still left which may produce extinction but are not important for the dynamics of the cluster.

3 RESULTS

Kroupa & Boily (2002) used a transformation function, $f_{\text{a,KB}}$, to transform the mass function of embedded clusters (ECMF) into the IMF of bound gas-free star clusters (ICMF). They used the following description:

$$ f_{\text{a,KB}}(M_{ecl}) = 0.5 - 0.4 \mathcal{G}(l M_{ecl}; \sigma_{M_{ecl}}; l M_{ecl}^{\text{exp}}), \tag{8} $$

with

$$ \mathcal{G}(l M_{ecl}; \sigma_{M_{ecl}}; l M_{ecl}^{\text{exp}}) = e^{- \frac{1}{2} \left( \frac{l M_{ecl} - l M_{ecl}^{\text{exp}}}{\sigma_{M_{ecl}}} \right)^2}, \tag{9} $$

and the constants $\sigma_{M_{ecl}} = 0.5$ and $l M_{ecl}^{\text{exp}} = \log_{10}(M_{ecl}^{\text{exp}}) = 4.0$. Thus, for example, at the mass $10^4 M_\odot$, $f_{\text{a,KB}} = 0.1$, that is, a $10^4 M_\odot$ cluster only retains 10 per cent of its stellar population according to this parametrization.

With the values from Table 1 it is now possible to define a similar quantity: but not a transformation function but transformation factors, $f_a$, for each observed star cluster. This is done by dividing the observed number of stars, $N_{\text{obs}}$, from Testi et al. (1999) and de Wit et al. (2004) by the calculated expected number of stars, $N_{\text{exp}}$. These values are listed in Table 1.

Fig. 2 shows the transformation function (equation 8) as the solid line and the derived transformation factors for each cluster from the

![Figure 2. Transformation factor as a function of embedded cluster mass for the sources from the Testi et al. (1999) sample (dots with solid error bars), the de Wit et al. (2004) sample (boxes with dashed error bars) and the de Zeeuw et al. (1999) sample (triangles with long-dashed error bars). For the Testi et al. (1999) and the de Wit et al. (2004) sample the upper ends of the ’error bars’ are determined for the cases with assumed extinction, while for the lower limit of the ’error bars’ no extinction was assumed. The errors for the de Zeeuw et al. (1999) sample are rather arbitrary – simply assuming a square root (Poisson) error in the observed number of OB stars in the association-cluster pairs. The solid line shows the transformation function (equation 8) adopted by Kroupa & Boily (2002). (See text.)](https://academic.oup.com/mnras/article-abstract/376/4/1879/1018375)

Testi et al. (1999) sample as the dots with solid error bars, from the de Wit et al. (2004) sample as the boxes with dashed error bars and from the de Zeeuw et al. (1999) sample as the triangles with long-dashed error bars. For the observations the case without extinction is used as a lower limit of the error bars and the case with extinction as an upper limit.

To reduce the scatter in the observations in Fig. 2 the lower and the upper limits on the $f_a$ values are combined separately into four mass bins. The results are shown in Fig. 3 for the Testi et al. (1999) sample only, in Fig. 4 for the combined Testi et al. (1999) and de Wit et al. (2004) sample, and in Fig. 5 for all three samples combined (de Zeeuw et al. 1999; Testi et al. 1999; de Wit et al. 2004). The dots connected by a dashed line are the lower limits and the boxes connected by a solid line are the upper limits. The error bars for the dots and boxes are the variances in each individual bin. Here again the solid line (without dots) is equation (8), the transformation function from Kroupa & Boily (2002).

The differences between Figs 3 and 4 are rather negligible – indicating a good agreement between the two samples. Because there are substantially larger uncertainties in the de Zeeuw et al. (1999) sample (ages, the mass of the most-massive star at 50 Myr, the transition mass between A and B stars, and the extrapolation from only 0.68 per cent of the stars to the total cluster population), it is not included in the further analysis.

In Fig. 4 it can be seen that the lower limits of the binned $f_a$ factors lie somewhat below equation (8), while the upper limits coincide with equation (8). Therefore, it might be plausible to reduce equation (8) to 0.4 for $M_{ecl} < 1000 M_\odot$. However, the large error bars in this investigation do not allow a further determination.

In a very recent publication (Wang & Looney 2007) the amount of young stellar objects (YSOs) around Herbig Ae/Be stars is further
studied with the use of archival 2MASS and Spitzer IRAC data. While most of their targets are already included in this study and the rest is too obscured by dust, the following additional data for VY Mon and VV Ser have been extracted. While they observed 26 stars for VY Mon (Testi: 25) and 22 for VV Ser (Testi: 24), they also gave number counts for YSOs in the whole observed field. In the case of VY Mon, they found 42 YSOs which is quite close to the 54 stars expected to be released by the cluster through gas expulsion (see Table 1). For VV Ser they found 148 YSOs. This is actually substantially higher than the expected number of 28, possibly due to other star-forming activity in that region.

4 DISCUSSION AND CONCLUSIONS

This contribution shows that with the use of available observational data (Testi et al. 1997, 1998, 1999; de Wit et al. 2004, 2005) it is possible to constrain the star loss due to gas expulsion in modest star clusters. The extracted upper and lower limits are shown in Fig. 4. The transformation function, $f_{\text{st}}$, is consistent with the upper end of the data. Thus, clusters with initial masses in the range $10^{-1} M_{\odot}$ appear to retain about 50 per cent of their stars, although the uncertainties are sufficiently large to allow even smaller retention fractions $f_{\text{st}}$. Therefore, such clusters would appear, in the stages after gas expulsion, as expanding associations.

In summary, cluster infant weight loss is generally rather high, all clusters with $M_{\text{ecl}} \lesssim 10^{3} M_{\odot}$ losing $\gtrsim 50$ per cent of their stars (Fig. 4). According to Kroupa & Boily (2002) infant weight loss may increase with cluster mass, but while being consistent with the present data this is not required by them, although the dashed constraints in Fig. 4 may be seen as lending some support to this notion. Further observations of these and other star-forming regions are needed to address the fraction of retained stars with more confidence.

ACKNOWLEDGMENTS

We thank an anonymous referee for valuable comments. This work has been funded by the Chilean FONDECYT grand 3060096. PK is grateful to the European Southern Observatory, Santiago, for being supported by a visiting fellowship in 2006 February and March, when this project was started. This research has made use of the WEBDA data base, operated at the Institute for Astronomy of the University of Vienna.

REFERENCES

