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Open cluster stability and the effects of binary stars

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ABSTRACT

The diagnostic age versus mass-to-light ratio diagram is often used in attempts to constrain the shape of the stellar initial mass function (IMF) and the potential longevity of extragalactic young to intermediate-age massive star clusters. Here, we explore its potential for Galactic open clusters. On the basis of a small, homogenised cluster sample, we provide useful constraints on the presence of significant binary fractions. Using the massive young Galactic cluster Westerlund 1 as a key example, we caution that stochasticity in the IMF introduces significant additional uncertainties. We conclude that, for an open cluster to survive for any significant length of time, and in the absence of substantial external perturbations, it is necessary but not sufficient to be located close to or (in the presence of a significant binary population) somewhat *below* the predicted photometric evolutionary sequences for "normal" simple stellar populations, although such a location may be dominated by a remaining "bound" cluster core and thus not adequately reflect the overall cluster dynamics.

Key words. Galaxy: open clusters and associations: individual: Westerlund 1, NGC 1976, Hyades, Coma Berenices, Orion Nebular Cluster – stellar dynamics – methods: observational – Galaxy: open clusters and associations: general

1. Introduction

Over the past few years, detailed studies of the stellar content and longevity of *extragalactic* massive star clusters have increasingly resorted to the use of the age versus mass-to-light ratio (M/L) diagram as a diagnostic tool, where one usually compares dynamically determined M/L's with those predicted by the evolution of "simple" stellar populations[1] (SSPs; e.g., Smith & Gallagher 2001; Mengel et al. 2002; McCrady et al. 2003; Larsen et al. 2004; McCrady et al. 2005; Bastian et al. 2006; Goodwin & Bastian 2006; de Grijs & Parmentier 2007; Moll et al. 2008). Based on high-resolution spectroscopy to obtain the objects' line-of-sight (1D) velocity dispersions, σ, and on high spatial resolution imaging to obtain accurate, projected half-light radii[2], $r_{\rm hl}$, most authors then calculate the dynamical cluster masses, $M_{\rm dyn}$, using

$$M_{\rm dyn} = \eta \frac{r_{\rm hl}\sigma^2}{G}, \quad (1)$$

where G is the gravitational constant (Limber & Mathews 1960; see also Aarseth & Saslaw 1972; Spitzer 1987). In Eq. (1), $\eta \approx 9.75$ is a dimensionless parameter which is usually assumed to be constant (but see Fleck et al. 2006; Kouwenhoven & de Grijs 2008). The dominant assumptions underlying the validity of Eq. (1) are that the cluster is in virial equilibrium, and that it consists of *single* stars of equal mass. While the latter assumption introduces an offset in the cluster mass of only approximately a factor of two compared to using a reasonable range of stellar masses (e.g., Mandushev et al. 1991; see also Fleck et al. 2006, and references therein), the former breaks down for ages younger than about 15 Myr. In reality, the effects of mass segregation (Fleck et al. 2006) and a high fraction of binary and multiple systems (Kouwenhoven & de Grijs 2008) also significantly affect the total cluster mass estimates obtained from integrated (whole-cluster) velocity dispersion measurements.

Nevertheless, using this approach one can get at least an initial assessment as to whether a given (unresolved) cluster may be (i) significantly out of virial equilibrium, in particular "super-virial"; (ii) substantially over- or underabundant in low-mass stars; or (iii) populated by a large fraction of binary and higher-order multiple systems. Since the work by Bastian & Goodwin (2006) and Goodwin & Bastian (2006), we can now also model any (super-virial) deviations from the SSP models for the youngest ages (up to ~40 Myr) if we assume that these are predominantly due to clusters being out of virial equilibrium after gas expulsion.

This has led a number of authors to suggest that, in the absence of significant external perturbations, massive clusters located in the vicinity of the SSP models and aged $\gtrsim 10^8$ yr may survive for a Hubble time and eventually become old globular cluster (GC)-like objects (e.g., Larsen et al. 2004; Bastian et al. 2006; de Grijs & Parmentier 2007).

Encouraged by the recent progress in this area based on both observational and theoretical advances, in this paper we set out to address the following unresolved questions:

1. *Can we use the integrated velocity dispersions of extragalactic massive star clusters as valid proxies of their*

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[1] As a "normal" SSP we define a coeval stellar population of a single metallicity and characterised by either a Salpeter (1955) or a Kroupa (2001)-type stellar initial mass function (IMF), i.e., a two-part power law covering the stellar mass range from 0.1 $M_\odot$ to ~125 $M_\odot$, depending on metallicity.

[2] Assuming that light traces mass, the observed half-light radii must be corrected for projection onto the sky by applying a correction factor of 3/4 (e.g., Fleck et al. 2006).

gravitational potential? To address this question we need to have access to the kinematics (as well as other physical properties) of the individual stars in a given set of sufficiently massive clusters. At present, the only massive cluster for which such data are available is the Galactic cluster Westerlund 1 (Sect. 3.2). Resolving this issue robustly is of prime importance in the field of extragalactic massive star cluster research, where it is implicitly assumed yet untested.

2. *Can we use the internal kinematics of Galactic open clusters to constrain their binary stellar populations in a straightforward manner?* To gain physical insights into this open issue crucial for stellar population modelling we obtained the relevant observations for a small sample of nearby open clusters for which proper motions and radial velocities were readily available for the individual member stars (Sect. 2). We derive the (apparent) dynamical M/L's and discuss their implications in Sects. 2 and 3. We particularly focus on the application of the new binary diagnostic diagram proposed by Kouwenhoven & de Grijs (2008).
3. *Is it sufficient for a cluster, based on resolved kinematic measurements, to be located close to the SSP model predictions in order for it to survive for any significant length of time, in the absence of external perturbations?* Given that this is a key underlying assumption in many extragalactic massive cluster studies, our approach in Sects. 3 and 4 is to revert this question: are there clear examples of clusters that satisfy this condition yet are known to be in the final stages of dissolution? If we can answer "yes" to the latter question, this will serve as a clear caution, as emphasised in Sect. 4, where we summarise our main results, cautions, and conclusions.

2. Observational data

In order to test the usefulness of the diagnostic diagram of cluster age versus M/L for Galactic open clusters (see Fig. 1, which we will discuss in detail in Sect. 3), we rely on published parameters. Since each of the observables has an associated uncertainty, it is paramount that we base our results on data sets that are as homogeneous as possible. The most crucial ingredient for the dynamical M/L determination is the internal velocity dispersion. We include only those Galactic open clusters for which these velocity dispersions have been derived from the proper motions of the individual stars[3] (for NGC 3532 the internal velocity dispersion used in this paper is based on individual stellar radial velocity measurements, Gieseking 1981). Where possible we include the *core* velocity dispersions, in order to match the structural parameters we will use. We also require well-determined distances (to obtain luminosities and linear velocity dispersions) as well as core radii and photometric observables. The distance estimates used here are mostly based on the recent homogenised compilations of Kharchenko et al. (2005) and Dias et al. (2006), supplemented with determinations based on a number of studies focusing on individual clusters. Although Kharchenko et al. (2005) provide values for the core radii of many of our sample clusters, the associated uncertainties are large. In fact, they often dominate our dynamical mass estimates, together with the often large uncertainties in the integrated V-band magnitudes. The latter are often difficult to obtain to any reasonable degree of accuracy because of the crowded fields in which many of the clusters are located and also because of uncertain stellar cluster membership determinations (see also the discussion in Sect. 3.2).

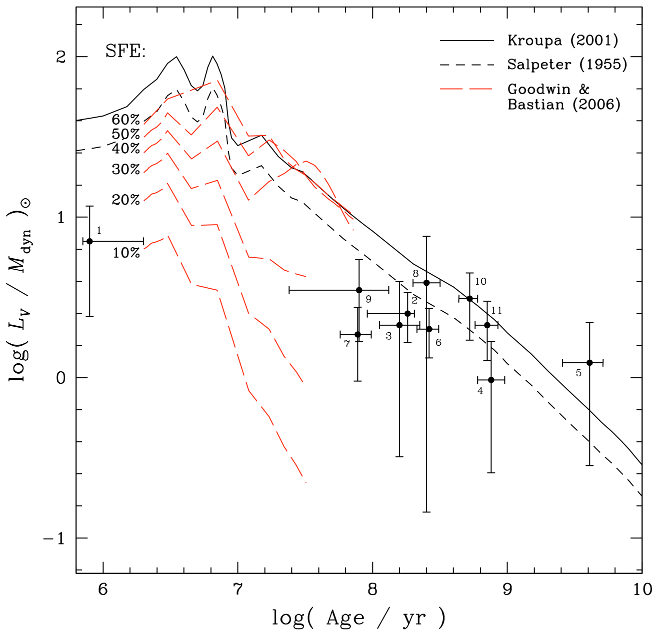

Fig. 1. Diagnostic age versus M/L_V diagram, including the Galactic open clusters for which velocity dispersion measurements are available. The evolution expected for SSPs governed by both Salpeter (1955) and Kroupa (2001) IMFs is shown as the solid and short-dashed lines, respectively. The long-dashed lines represent the evolution expected for SSPs with a Kroupa (2001)-type IMF, but a range of effective star-formation efficiencies (Goodwin & Bastian 2006). The sizes of the error bars are based on the most realistic ranges of observable values used to calculate the clusters' loci in this diagram. Numbered clusters: 1, NGC 1976 (Orion Nebula Cluster); 2, NGC 2168; 3, NGC 2516; 4, NGC 2632; 5, NGC 2682; 6, NGC 3532; 7, NGC 5662; 8, NGC 6705; 9, Pleiades; 10, Coma Berenices; 11, Hyades.

Nevertheless, in Table 1 we have collected the "best" values for the core radii, R_c, distances, D, apparent V-band magnitudes, foreground extinction, $E(B-V)$, and velocity dispersions, σ. We also list their likely (uncertainty) ranges for our sample clusters. We provide for both the values and the uncertainties the references we have used, and we have aimed to homogenise our cluster sample parameters (following a similar procedure as Paunzen & Netopil 2006, although they used different selection criteria). This implies that our choice of the "best" values for certain parameters may depend on the values of one or more of the other observables. We provide the full list of references used to obtain the most likely parameter ranges. However, where we have discarded certain values (often because they were clear statistical outliers), the relevant respective references are bracketed.

In Table 2 we list the best ages and their uncertainty ranges of our sample clusters using the same notation as in Table 1, as well as the total cluster masses – based on Eq. (1), with $\eta = 9.75$ – and their L_V/M ratios derived based on the parameters and their ($\sim 1\sigma$) uncertainties from Table 1. A full list of references to Tables 1 and 2 is provided in Table 3.

We note that our sample selection is biased towards the nearest Galactic open clusters, for which reasonably accurate internal velocity dispersions could be obtained. However, although our sample is by no means complete in any sense, we can still use it to assess (i) the binary fractions of the clusters individually (Sect. 3); and (ii) the usefulness of the diagnostic age versus M/L diagram for cluster longevity considerations (Sect. 4).

[3] Although, strictly speaking, Eq. (1) is valid for line-of-sight velocity dispersions instead of the equivalent dispersions based on proper-motion studies, the effect of ignoring this will be mass overestimates by a factor of 2 (or $\Delta \log L/M = +0.3$) if the clusters' kinematics are isotropic. This does not affect our conclusions.

Table 1. Observational parameters of the open cluster sample.

Name	R_c		±		D		±		V		±		$E(B-V)$		±		σ		±	
	(arcmin)	Ref.	(arcmin)	Ref.	(pc)	Ref.	(pc)	Ref.	(mag)	Ref.	(mag)	Ref.	(mag)	Ref.	(mag)	Ref.	(km s^{-1})	Ref.	(km s^{-1})	Ref.
NGC 1976	7.2	38	2.4	13	470	13 38	70	9, 20, 45	1.26	21	0.1	[a]	0.05	9, 20	0.01	[a]	2.34	45	0.7	17, 45
NGC 2168	12.0	20	1.2	[a]	912	9 19	68	3, 9, 19, 20 26, 42, 43	4.86	42, 43	0.2	[a] (3)	0.20	9, 19	0.05	3, 20, 35, 39 42, 43, 47	1.00	26	0.10	26
NGC 2516	12.0	20	1.8	[a]	358	41	60	3, 6, 9 20, 42, 43	3.1	[b]	0.3	3, 35	0.11	41	0.02	7, 9, 20, 35 41, 42, 43	1.35	33	0.35	33
NGC 2632	66.0	15	4.0	20	171	31	12	2, 9, 20 31	3.2	39	0.1	3, 35	0.00	31, 35 39	0.01	9, 20, 36	0.48	16	0.2	16
NGC 2682	4.7	4	0.6	4	820	31	47	31, 36, 37 42, 43	6.5	36	0.3	35, 39 42, 43	0.05	31	0.02	9, 20, 31, 35, 36 39, 42, 43, 44	0.81	12	0.4	12, 25
NGC 3532	12.0	20	1.2	[a]	492	31	8	3, 9, 20, 31	3.1	3	0.2	[a]	0.04	3, 20 31	0.01	5, 9, 31	1.49	11	0.29	11
NGC 5662	6.0	20	1.2	[a]	684	31	60	9, 20, 31, 34 42, 43	5.6	30	0.2	[a]	0.32	30, 31 42, 43	0.01	9, 20, 31, 34	1.2	33	0.3	33
NGC 6705	1.38	27	0.90	8, 20 23, 27	2042	40	150	3, 8, 9, 20 27, 40, 42, 43	6.8	27	0.4	3, 42 43	0.43	9, 20 40	0.03	3, 8, 30, 39, 40 42, 43	2.0	26	0.8	24, 25
Pleiades	66.0	1 20	9.0	1	133	31	9	9, 20, 31	1.2	35	0.1	39	0.05	31	0.01	9, 20, 31, 35, 39	0.6	26	0.2	15
Coma Ber	96.0	28	9.0	20, 28	86	31	7	9, 20, 28, 31	1.8	35	0.2	[a]	0.00	20, 31 35	0.01	9, 31	0.3	28	0.2	[a]
Hyades	205.8	32	2.0	[a]	42	31	3	9, 31	0.5	[b]	0.1	35, 39	0.00	31, 35 36, 39	0.01	9, 31	0.32	22	0.2	[a]

Notes. [a] Adopted based on realistic measurement errors for large samples of open clusters (Dias et al. 2002; and unpublished); [b] average.

Table 2. Derived parameters of the open cluster sample

Name	log(Age yr^{-1})	Ref.	±	Ref.	$M_{\rm dyn}(M_\odot)$	$\log(L_V/M_{\rm dyn})[L_{V,\odot}/M_\odot]$
NGC 1976	5.90	38	$^{+0.40}_{-0.05}$	(9, 20), 29	9400 ± 5250	$0.85^{+0.22}_{-0.47}$
NGC 2168	8.26	9, 18	$^{+0.05}_{-0.30}$	3, 20, 39, 42, 43, 47	5551 ± 1047	$0.40^{+0.13}_{-0.18}$
NGC 2516	8.2	41	0.15	3, 6, 9, 20, (42, 43)	3970 ± 1680	$0.33^{+0.27}_{-0.82}$
NGC 2632	8.88	31	0.10	2, 9, 20, 31, 36, (39)	1319 ± 920	$0.02^{+0.25}_{-0.59}$
NGC 2682	9.61	31	$^{+0.10}_{-0.20}$	9, 10, 14, 20, 31, 36 37, 39, 42, 43, 46	1277 ± 907	$0.10^{+0.25}_{-0.64}$
NGC 3532	8.42	31	$^{+0.07}_{-0.09}$	3, 5, 9, 20, 31	6649 ± 1950	$0.30^{+0.13}_{-0.18}$
NGC 5662	7.89	31	$^{+0.10}_{-0.13}$	9, 20, 30, 31 34, 42, 43	2998 ± 1246	$0.27^{+0.17}_{-0.29}$
NGC 6705	8.4	9, 40	0.1	3, (8), 20, 27 (30, 39), 42, 43	5717 ± 4956	$0.59^{+0.29}_{-1.43}$
Pleiades	7.90	31	$^{+0.22}_{-0.52}$	9, 20, 31, 39	1603 ± 794	$0.54^{+0.19}_{-0.32}$
Coma Ber	8.72	31	$^{+0.06}_{-0.08}$	9, 20, 28, 31	377 ± 112	$0.49^{+0.16}_{-0.26}$
Hyades	8.85	31, 36	$^{+0.08}_{-0.09}$	9, 31, 39	450 ± 170	$0.33^{+0.15}_{-0.22}$

3. The dynamical state of Galactic open clusters

3.1. Open clusters in the diagnostic diagram

Using the observational data from Sect. 2, we applied Eq. (1) to derive the dynamical masses for each of our sample cluster cores and calculated the relevant M/L_V's. Their loci in the diagnostic diagram are shown in Fig. 1. Overplotted is the expected evolution of SSPs (Maraston 2005) for both a Salpeter (1955) and a Kroupa (2001) stellar IMF (solid and short-dashed lines, respectively).

We have also included the expected evolution of clusters formed with a variety of *effective* star-formation efficiencies (eSFEs; Goodwin & Bastian 2006). The eSFE is a measure of the extent to which a cluster is out of equilibrium after gas expulsion, on the basis that the virial ratio *immediately before* gas expulsion was $Q_{\rm vir} = T/|\Omega| = 1/2({\rm eSFE})$ (where T and Ω are the kinetic and potential energy of the stars, respectively, and a system in virial equilibrium has $Q_{\rm vir} = 1/2$). The eSFE corresponds to the true SFE if the stars and gas were initially in virial equilibrium (see Goodwin & Bastian 2006).

Owing to the nature of our sample, only[4] the Orion Nebula Cluster (ONC, cluster 1 in Fig. 1) is currently young enough so as to possibly be affected by the effects of rapid gas expulsion, as shown by the extent (in terms of age) of the long-dashed lines in Fig. 1. The majority of our sample clusters are old enough ($\gtrsim$40 Myr) to have re-virialised after gas expulsion. The dynamical state of these objects is therefore dominated by the combined effects of (internal) two-body relaxation, binary motions, and external perturbations.

The fact that our sample of surviving open cluster cores lie close to the SSP predictions should be expected. Clusters significantly below the SSP lines will be dynamically "hot" and are expected to dissolve rapidly, whilst clusters significantly above the lines will be dynamically "cold" and should (re-)virialise over a few crossing times to move closer to the canonical SSP lines.

We will now explore the reasons as to why most of our sample clusters (cores) are found somewhat below the SSP model

[4] Despite the extent of the error bar associated with the age estimate of the Pleiades, Kroupa et al. (2001) showed this cluster to have re-virialised by an age of 50 Myr, so that it is unlikely affected by the aftermath of the gas-expulsion phase.

Table 3. References to Tables 1 and 2.

No.	Reference	No.	Reference	No.	Reference	No.	Reference
1	Adams et al. (2001)	13	Hillenbrand & Hartmann (1998)	25	McNamara & Sanders (1977)	37	Sandquist (2004)
2	Adams et al. (2002)	14	Hurley et al. (2005)	26	McNamara & Sekiguchi (1986)	38	Scally et al. (2005)
3	Batinelli et al. (1994)	15	Jones (1970)	27	Nilakshi et al. (2002)	39	Spassova & Baev (1985)
4	Bonatto & Bica (2003)	16	Jones (1971)	28	Odenkirchen et al. (1998)	40	Sung et al. (1999)
5	Clariá & Lapasset (1988)	17	Jones & Walker (1988)	29	Palla & Stahler (1999)	41	Sung et al. (2002)
6	Dachs & Kabus (1989)	18	Joshi & Sagar (1983)	30	Pandey et al. (1989)	42	Tadross (2001)
7	Dambis (1999)	19	Kalirai et al. (2003)	31	Paunzen & Netopil (2006)	43	Tadross et al. (2002)
8	Danilov & Seleznev (1994)	20	Kharchenko et al. (2005)	32	Perryman et al. (1998)	44	Taylor (2007)
9	Dias et al. (2002)	21	Kopylov (1952)	33	Sagar & Bhatt (1989)	45	van Altena et al. (1988)
10	Dinescu et al. (1995)	22	Makarov et al. (2000)	34	Sagar & Cannon (1997)	46	VandenBerg & Stetson (2004)
11	Gieseking (1981)	23	Mathieu (1984)	35	Sagar et al. (1983)	47	von Hippel et al. (2002)
12	Girard et al. (1989)	24	Mathieu (1985)	36	Salaris et al. (2004)		

curves (i.e., they seem somewhat supervirial with respect to the expectations from the SSP models), irrespective of whether or not they actually follow the SSP predictions or are characterised by roughly constant M/L's as a function of age. We expect errors in the core radii to be random, and unbiased by the mass of a cluster. However, the use of the *core* velocity dispersions and radii may introduce a systematic bias in the dynamical mass estimates.

There are three dynamical effects that could affect the position of the clusters relative to the SSP predictions.

First, equipartion and mass segregation could lower the core velocity dispersion relative to the "typical" velocity and hence move the clusters' positions to above the SSP predictions. The majority of the star clusters in our sample are older than $\sim 10^8$ yr, which implies that they have ages greater than their half-mass relaxation times (see, e.g., Danilov & Seleznev 1994, for the relevant time-scales for most of our sample clusters). Therefore, these clusters (and particularly their cores) are expected to be close to energy equipartition, and thus are significantly mass segregated – as observed for, e.g., NGC 2168 (Sung & Bessell 1999; Kalirai et al. 2003), NGC 2682 (Bonatto & Bica 2003), and NGC 6705 (e.g., Sung et al. 1999, and references therein) among our present sample. Equipartition reduces the *global* velocity dispersion of high-mass stars relative to low-mass stars, causing high-mass stars to migrate to the cluster core. Therefore, we might expect the core velocity dispersion of low-mass cores (as characteristic for the open clusters discussed in this paper) to underestimate the dynamical mass of the clusters as a whole and thus produce colder clusters[5] – as seen in Fig. 1 (although we remind the reader of the expected re-virialisation discussed above; this may introduce an observational bias in the sense that we would not be able to detect low-mass cluster cores that are significantly super-virial and hence – possibly – in the process of dissolution).

Secondly, the clusters' mass functions (MFs) will have been altered by dynamical evolution, with the preferential loss of low-mass stars moving clusters to above the SSP predictions. This will result in a "top-heavy" MF in clusters, which will in turn lead to lower M/L_V's than would be expected from the canonical SSP models. The degree to which the MF will change depends on the two-body relaxation time which, to first order, depends on the mass of the cluster (and also on its size; however, we ignore this for now). Thus, old low-mass clusters are expected to have top-heavy MFs compared to old high-mass clusters. Therefore, we would expect low-mass clusters to lie some way above the canonical SSP models, and high-mass clusters to lie slightly above these lines[6].

Thirdly, the presence of binaries may result in an observed velocity dispersion that is higher than the "true" value, moving the clusters to below the SSP predictions. Kouwenhoven & de Grijs (2008) pointed out that if the velocity dispersion of binary systems was similar to the velocity dispersion of the cluster (core) as a whole, the *observationally measured* velocity dispersion would overestimate the mass of a cluster. We can explore, to first order, whether the binary population may be a significant factor causing an offset in Fig. 1 by using the new diagnostic proposed by Kouwenhoven & de Grijs (2008, their Fig. 9). In Fig. 2 we reproduce the main features of their Fig. 9, and include our open cluster sample (using the clusters' core radii instead of their half-mass radii; the core radii are more likely to represent the size of the bound stellar population for these clusters; see, e.g., Odenkirchen et al. 1998, for arguments relating to the open cluster in Coma Berenices). It is immediately clear from the location of the data points that the vast majority of our sample clusters are indeed expected to be significantly affected by binaries ($\eta > 9.75$, cf. Fig. 2; in fact, the data points represent upper limits to the cluster masses given that we do not know the intrinsic masses but need to rely on dynamical tracers). This seems to be borne out by relevant recent observations of a number of our sample clusters, including NGC 2516 (cf. Sung et al. 2002), NGC 2632 (M 44, also known as the Praesepe cluster: see, e.g., Bouvier et al. 2001; Patience et al. 2002, and references therein), the Pleiades (e.g., Martin et al. 2000, and references therein), and the Hyades (e.g., Stefanik & Latham 1992; Patience et al. 1998).

[5] For a quantitative estimate of this effect, let us assume that our clusters are well represented by Plummer models. However, we note that this is an unproven assumption; younger clusters are likely more extended (e.g. Elson et al. 1987), whereas older clusters (particularly lower-mass objects) may be significantly depleted in their outer regions and hence could be much more compact. A back-of-the-envelope calculation shows then that the following relations apply (from Heggie & Hut 2003): $R_{\rm c,intr} = R_{\rm hm,proj}/\sqrt{2}$, $R_{\rm virial} = R_{\rm hm,proj} \times 16/3\pi$, and $R_{\rm hm,intr} \simeq 1.305 R_{\rm hm,proj}$. This leads, approximately, to $R_{\rm c,intr} \simeq 1.035 R_{\rm c,proj}$, and therefore $R_{\rm hm,proj} \simeq 1.464 R_{\rm c,proj}$. Here, the subscripts "c", "hm", "intr", and "proj" stand for core, half mass, intrinsic, and projected. This result only holds *approximately* for a Plummer model; it gives us a rough idea of the errors involved in our analysis, leading to $\Delta(L_V/M_{\rm dyn}) \sim -0.165$ (in solar units).

[6] However, we need an unbiased sample to explore this option statistically and in more detail.

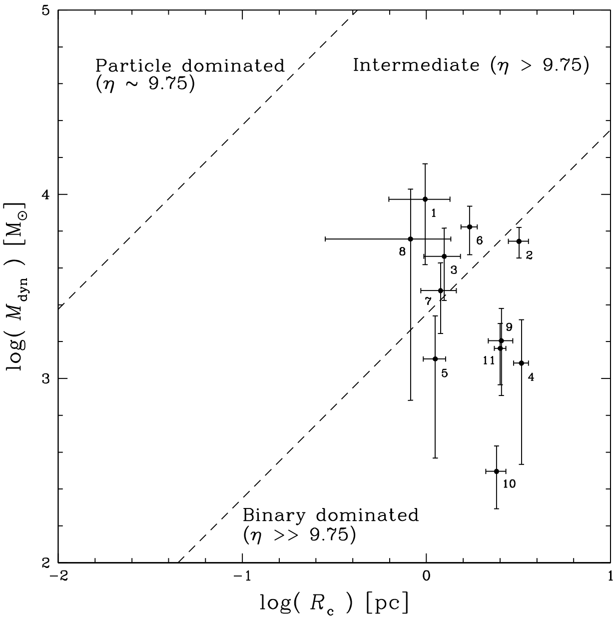

Fig. 2. Diagnostic $R_{\rm c}$ versus $M_{\rm dyn}$ diagram, following Kouwenhoven & de Grijs (2008), including our sample open clusters. The basic data used to generate the data points and their uncertainties is included in Tables 1 and 2; the cluster numbers correspond to those in Fig. 1.

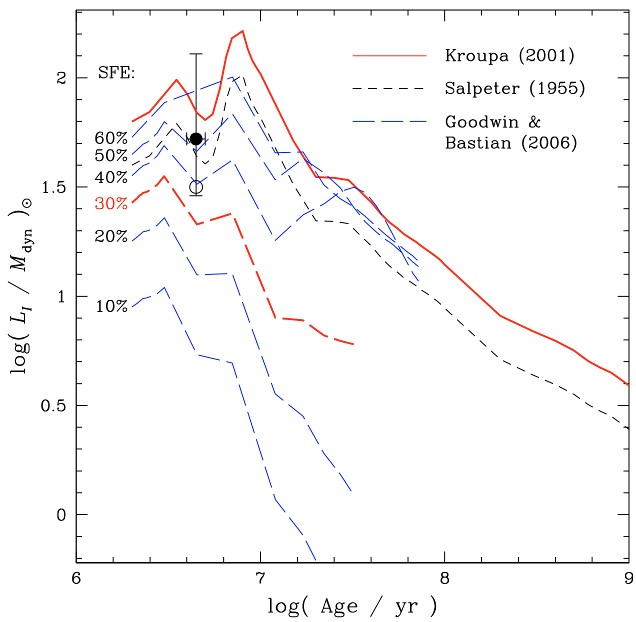

Fig. 3. Westerlund 1 in the diagnostic age versus M/L_V diagram. The open circle represents the cluster's locus if we were to exclude the nine brightest stars; this exemplifies the uncertainties introduced by stochastic IMF sampling and by having fortuitously caught the cluster at a time when it is dominated by a small number of very bright stars. The line coding is as in Fig. 1.

That the cluster cores appear to lie below the SSP predictions seems to suggest that the effect of binaries outweighs mass segregation and the change in the MF in determining the position of the cluster cores in the diagram. As shown by Kouwenhoven & de Grijs (2008), this is to be expected for relatively low-mass open clusters such as the objects we are considering here. However, without a detailed investigation of each cluster and their component stars, it is impossible to reconstruct the degree to which each effect is important. However, we argue that it seems clear that the position of most clusters (cores) below the canonical SSP lines is not due to significant deviations from virial equilibrium.

Finally, we also note that we may well have overestimated the masses by factors of a few through the universal use of Eq. (1). For highly mass-segregated clusters containing significant binary fractions, a range of stellar IMF representations, and for combinations of characteristic relaxation time-scales and cluster half-mass radii, the adoption of a single scaling factor $\eta \approx 9.75$ introduces systematic offsets, leading to lower values of η (e.g., Fleck et al. 2006; Kouwenhoven & de Grijs 2008), and thus to dynamical mass overestimates if $\eta = 9.75$ were assumed. However, the uncertainties are too large at the present time to reach firm conclusions regarding the dependence of our results on η.

3.2. Westerlund 1

The Galactic young massive star cluster, Westerlund 1 (aged 4–5 Myr; Crowther et al. 2006), and in particular its stellar content, has been the subject of considerable recent attention (e.g., Clark et al. 2005, 2008; Crowther et al. 2006; Muno et al. 2006; Mengel & Tacconi-Garman 2007a,b; and references therein). It is the nearest potential GC progenitor, and certainly the most massive young Galactic cluster ($M_{\rm cl} \simeq 10^5\ M_\odot$, with an absolute lower limit of $M_{\rm cl,low} \simeq 1.5 \times 10^3\ M_\odot$; Clark et al. 2005; see also Mengel & Tacconi-Garman[7] 2007a). In order for the cluster to survive, it cannot have a stellar IMF that is deficient in low-mass stars. Given that all observed star clusters exhibit a range in stellar masses, we conclude that the Westerlund 1 IMF must therefore be close to "normal" (there is no conclusive evidence of clusters with "bottom-heavy" IMFs, which could potentially also lead to the cluster's position in Fig. 3). In de Grijs & Parmentier (2007) we reviewed the balance of evidence (e.g., Muno et al. 2006; Clark et al. 2008), but the results remained inconclusive because of the difficulty of observing the cluster's low-mass stellar population. Brandner et al. (2008) recently completed a detailed study of the cluster's mass function down to $\sim 1\ M_\odot$, which appears to be consistent with a normal Kroupa or Salpeter-type IMF.

In addition, the relaxation of an idealised cluster and the contribution of the most massive stars to the escape of stars below a typical limiting (high) mass scales approximately in a power-law fashion (with a power $\gtrsim 3$) with mass (e.g., Hénon 1969, and references therein). This is key to understanding the dynamical importance of a particular IMF. It follows that the escape rate of low-mass stars below a certain mass is mass-independent. Moreover, in an equilibrium system the number of stars escaped from the cluster by an age of 4 Myr would therefore be small and hardly affect the overall shape of the IMF. Hence, only a small modification of the IMF below the supernova mass limit would be expected at the present age, and the observed IMF will therefore be close to "normal".

Using the dynamical mass estimate from Mengel & Tacconi-Garman (2007a), combined with the integrated photometry of

[7] Although these authors published a mass determination of $M_{\rm cl} = 6.3^{+5.3}_{-3.7} \times 10^4\ M_\odot$ for Westerlund 1, they recently redetermined its velocity dispersion and hence its mass, at $M_{\rm cl} \sim 1.25 \times 10^5\ M_\odot$ (Mengel & Tacconi-Garman 2007b).

Piatti et al. (1998), we reached a similar conclusion (de Grijs & Parmentier 2007), despite the significant uncertainties in the observables. Since in the V band, on which the Piatti et al. (1998) photometry was based, the confusion between the cluster members and the Galactic field stellar population is substantial (in essence because of the significant extinction along this sightline), we obtained imaging observations at longer wavelengths, where this confusion is significantly reduced. An I-band (peakup) image of the cluster (using the Ic/Iwp-ESO0845 filter), with an exposure time of 3.0 s, was obtained with the ESO 2.2 m telescope equipped with the Wide-Field Imager (WFI) at La Silla Observatory (Chile). The image was kindly made available to us by Crowther. Using the photometric zero-point offsets of Clark et al. (2005) we obtained an integrated I-band magnitude of $m_I = 6.15 \pm 0.05$ mag within a radius of 108 arcsec. This includes all of the bright cluster members and excludes bright foreground sources.

The combined integrated magnitude of the three brightest red supergiants (objects 26, 237, and 20 of Clark et al. 2005, in order of decreasing brightness), yellow hypergiants (objects 32, 4, and 8) and blue supergiants (objects 243, 16, and 7) is $m_I = 7.15 \pm 0.05$ mag. Therefore, these nine sources alone contribute some 40% of the cluster's total integrated I-band flux. Each of these sources is in a rare, short-lived phase and so the luminosity of the cluster might be expected to vary significantly on short time-scales. In addition, we specifically discuss these nine brightest cluster members separately, because these are the stars that make Westerlund 1 one of the most unusual young star clusters known (e.g., Clark et al. 2005, 2008; Crowther et al. 2006). These nine sources stand out from the overall stellar luminosity function, which appears to otherwise have been drawn from a "normal" IMF. Thus, this serves as a clear caution that stochasticity in the cluster's IMF (e.g., Brocato et al. 2000), as well as stochasticity in the numbers of stars in unusually luminous post-main-sequence evolutionary stages (e.g., Cerviño & Valls-Gabaud 2003; Cerviño & Luridiana 2006) may contribute significantly to variations in a cluster's observed M/L. On a related note, we caution that the luminosities of *all* of the clusters we analyse in this paper are subject to stochastic effects, regardless of their age (Cerviño & Valls-Gabaud 2003; Cerviño & Luridiana 2006).

Using the most up-to-date distance to Westerlund 1, $D = 3.9 \pm 0.7$ kpc (Kothes & Dougherty 2007), a V-band extinction of $A_V = 11.6$ mag (Clark et al. 2005), and the Galactic reddening law of Rieke & Lebofsky (1985, resulting in $A_I = 5.6$ mag), we obtain the locus in (age versus L/M ratio) space as shown in Fig. 3. Despite the large error bars and very young age, it appears at first sight that Westerlund 1 is not significantly out of virial equilibirum. Its location in Fig. 3 is consistent with the cluster having formed with a high eSFE, and with a Kroupa or Salpeter-like stellar IMF. Given the different filters used between Piatti et al. (1998) and this paper, and in view of the updated cluster mass estimate, this result confirms our earlier assertion in de Grijs & Parmentier (2007) based on the cluster's location in the M/L_V versus age diagram (which in turn supported the conclusion of Mengel & Tacconi-Garman 2007a, that the cluster appears to be close to virial equilibrium). However, we note that it is not entirely clear if Westerlund 1 would be expected to be in virial equilibrium. Bastian et al. (2008) show that observations of massive young clusters suggest that they may expand from initial half-mass radii of ~0.1 pc to >1 pc in the first few Myr of their lives (see, in particular, their Fig. 4). In such a situation we might expect Westerlund 1 to lie well below the canonical IMF lines.

If we were to exlude the nine brightest stars making up some 40% of the cluster's integrated I-band flux, its locus would shift to that of the open circle (assuming that the cluster's mass remains unchanged). We will now briefly explore whether this effect would be significantly different in the V band, as discussed in de Grijs & Parmentier (2007). Although we do not have unsaturated V-band images of Westerlund 1, we can use the results of Piatti et al. (1998, their Fig. 8) to check the above statements to first order. We base our analysis on the simplistic assumption that the innermost nine stars are the nine brightest stars.

Based on this figure, the nine innermost stars contribute a combined $M_V \sim -9.8$ mag; the full integrated cluster magnitude is $M_{V,\rm tot} \sim -11.2$ mag. We therefore conclude that these nine innermost stars contribute ~30% of the cluster's total luminosity. Some, but not all, of these stars are clearly the very bright stars we used in our I-band analysis, so that this estimate provides a lower limit to the contribution of the nine brightest stars. Given that we found that in the I band the nine brightest stars contribute ~40% of the total flux, the V and I-band contributions of the nine brightest stars are similar, particularly in view of the uncertainties. In fact, this could have been expected – to first order – because the spectral energy distributions of each of the three subgroups (blue and red supergiants and yellow hypergiants) peak at different wavelengths. Therefore, stochasticity remains a serious issue across these wavelengths, simply because these stars are intrinsically so bright.

This shows the potential effects of (i) stochastic sampling of a cluster's IMF (predominantly affecting the highest-mass end in any cluster); and (ii) having caught the cluster at a time when it is dominated by a few very luminous yet short-lived stars. If indeed we are fortuitous in having observed a stochastically exceptional situation regarding the numbers of very massive (bright) stars in the cluster, it would indicate that Westerlund 1 may have formed with an eSFE around the ~30–40% required for clusters to survive the gas expulsion phase (e.g., Lada et al. 1984; Goodwin 1997a,b; Adams 2000; Geyer & Burkert 2001; Kroupa & Boily 2002; Boily & Kroupa 2003a,b; Fellhauer & Kroupa 2005; Bastian & Goodwin 2006; Parmentier & Gilmore 2007, their Fig. 1), although we note that the error bars are large and will remain unchanged by the removal of these nine brightest stars. As an aside, we note that differential extinction towards the individual brightest cluster stars is not an issue; extinction variations along individual sight lines are minimal, with deviations from a mean $K_{\rm s}$-band extinction of $\Delta(A_{K_{\rm s}}) = 0.14$ mag (e.g., Crowther et al. 2006); this narrow spread is due to the extinction estimates being based on assumed intrinisic stellar colours, which in reality vary slightly.

3.3. The Orion Nebula Cluster

The dynamical state of the core of the Orion Nebula Cluster (NGC 1976, M 42; cluster 1 in Fig. 1) has been the subject of significant observational and theoretical investigations (e.g., Hillenbrand & Hartmann 1998; Kroupa et al. 1999; Kroupa 2000; Kroupa et al. 2001; O'Dell 2001; Scally et al. 2005, and references therein). It is the youngest cluster in our sample and is located (~3σ) below the "normal" SSP evolution in Fig. 1, even in view of the uncertainties. This super-virial state is corroborated by current estimates of its virial ratio, which suggest that the cluster (core) is already unbound, but has only recently become so (e.g., Kroupa et al. 2001; Scally et al. 2005). In fact, Hillenbrand & Hartmann (1998) showed that in order for the ONC to be in virial equilibrium, based on the cluster's observed velocity dispersion, the total mass within about 2 pc of the central "Trapezium" configuration of massive stars must be of order twice that of the known stellar population in the region (and comparable to the estimated mass in molecular gas projected onto the area). Given the youth of the cluster, and its partially embedded nature, Hillenbrand & Hartmann (1998) argued that if $\gtrsim$20% of the remaining molecular gas is converted into stars, this might result in a gravitationally bound cluster. Follow-up *N*-body simulations led Scally et al. (2005) to conclude that the size and age of the ONC imply that either the cluster is marginally bound (or has become unbound only very recently), or else that it has expanded quasi-statically. Kroupa et al. (2001), on the other hand, performed binary-rich *N*-body models of the ONC adopting two of the allowed initial configurations from Kroupa (2000) and showed that it is currently expanding and was probably formed with an eSFE near 33%. In view of the uncertainties, this is roughly consistent with its locus in the diagnostic diagram of Fig. 1.

3.4. Dissolving clusters

3.4.1. Coma Berenices

Odenkirchen (1998) found that the open cluster in Coma Berenices (cluster 10 in Fig. 1) has an elliptical core-halo morphology, combined with a group of extratidal stars either escaping stars or genuine field stars; see also Küpper et al. (2008), for a general discussion on the distribution of escaped stars), which are located at projected distances of $\geq$10 pc from the cluster centre. They provide some tentative evidence of the presence of an additional population of even lower-mass extratidal stars, and argue that the existence of this significant population of stars beyond the cluster's tidal radius is evidence of the cluster dissolution process caught in the act. At the same time, they conclude that – given the present mass and configuration of the cluster stars – the observed (core) velocity dispersion is fully consistent with the expectations from the SSP models.

Here we reach, in essence, the same conclusion. Based on the observational data at hand, the core of the star cluster in Coma Berenices is located very close to the expected photometric evolutionary sequences in Fig. 1, within reasonably small uncertainties. Given that there is evidence that this cluster is in the advanced stages of dissolution, this result should be considered as a strong caution. It appears that for a cluster to survive for a significant length of time, it is a necessary, but *not a sufficient condition* for it to be located close to the evolutionary sequences in our diagnostic diagram. We caution, however, that since our velocity dispersion measurements were weighted towards the central region of the cluster, it is possible that the cluster's locus in Fig. 1 mainly reflects its remaining bound component.

3.4.2. The Hyades

The Hyades (cluster 11 in Fig. 1) is a dynamically very evolved, marginally bound cluster significantly depleted in low-mass stars (e.g., Kroupa 1995; Perryman et al. 1998; see also Portegies Zwart et al. 2001), with a stellar velocity dispersion of order 0.3–0.4 km s^{-1} (Makarov et al. 2000; see also Madsen 2003). Detailed *N*-body simulations (e.g., Terlevich 1987; Madsen 2003; Chumak et al. 2005) indicate that a halo of gravitationally unbound stars can still be linked with the cluster, and that these stars are moving along with it on similar orbits (cf. Küpper et al. 2008), for several $\times10^8$ yr (see Perryman et al. 1998, for a detailed discussion). Hence, at its current age of $\log t(\mathrm{yr}) = 8.85^{+0.08}_{-0.09}$ (Paunzen & Netopil 2006, and references therein) it is not surprising that the Hyades moving group is still detectable as a cluster-type object.

In Fig. 1, the Hyades occupies a locus very close to the evolutionary sequences (and with small error bars), yet the group is likely (i) unbound overall; and (ii) in the final stages of dissolution (Odenkirchen et al. 1998). Although the same caution applies to the Hyades moving group as to the cluster in Coma Berenices, we conclude again that for a cluster to survive for a significant length of time, it is a necessary, but *not a sufficient condition* for it to be located close to the evolutionary sequences in our diagnostic diagram.

4. Discussion and conclusions

In this paper, we have explored the usefulness of the diagnostic age versus M/L diagram in the context of Galactic open clusters. This diagram is often used in the field of extragalactic young to intermediate-age massive star clusters to constrain the shape of their stellar IMF, as well as their stability and the likelihood of their longevity.

Using a sample of Galactic open clusters for which reasonably accurate internal (core) velocity dispersions are available in the literature, we constructed a homogenised set of observational data drawn from a wide variety of publications, also including their most likely uncertainty ranges. This allowed us to derive dynamical mass estimates for our sample of open clusters, as well as their respective M/L_V's and – crucially – the associated (realistic) uncertainties.

It seems clear that the effect of binaries, mass segregation, and the dynamical alteration of mass functions by two-body relaxation are important constraints that cannot be ignored.

Using the massive young Galactic cluster Westerlund 1 as a key example, we caution that stochasticity in the IMF introduces significant additional uncertainties. Therefore, the stability and long-term survival chances of Westerlund 1 remain inconclusive.

Most importantly, however, we conclude that for an open cluster to survive for any significant length of time (in the absence of substantial external perturbations), it is a necessary but not a sufficient condition to be located close to the predicted photometric evolutionary sequences for "normal" SSPs. This is highlighted using a number of our sample clusters (and the parameters related to the cluster cores) which are known to be in a late stage of dissolution, and lie very close indeed to either of the evolutionary sequences defined by the Salpeter (1955) or Kroupa (2001) IMFs. However, we also note that a fair fraction of our sample clusters show the signatures of dynamical relaxation and stability. Among our current sample, these include NGC 2168 (M 35, Kalirai et al. 2003), NGC 2682 (M 67, Hurley et al. 2005), NGC 6705 (M 11, Mathieu 1984; McNamara & Sekiguchi 1986; Sung et al. 1999) and the Pleiades (M 45; McNamara & Sekiguchi 1986; Pinfield et al. 1998; Raboud & Mermilliod 1998). Despite their relatively low masses ($M_{\rm cl} \lesssim 2\times10^3\ M_\odot$) and ages in excess of a few $\times10^8$ yr, this is not unexpected.

Using the vertical oscillation period, π, around the Galactic plane of NGC 2323 ($\pi \approx 50$ Myr; Clariá et al. 1998) as an example, this cluster has only been through a few of these periods, given its age of $\log t(\mathrm{yr}) = 8.11^{+0.05}_{-0.25}$ (Kalirai et al. 2003). However, at the Galactocentric distance of the Sun, a Pleiades-like open cluster crosses the Galactic disc approximately 10–20 times before it dissolves (de la Fuente Marcos 1998a,b). The models of Kroupa et al. (2001), which match the ONC at an age of 1 Myr very well, as well as the Pleiades at 100 Myr, suggest that these objects would end up below the evolutionary sequences in Fig. 1, despite having started from the Kroupa (2001) IMF at birth. The deviation may have been caused by the heating of the clusters by the Galactic tidal field. In other words, it seems that the velocity dispersion is always somewhat higher after Galactic-plane passage, because the stars suffer from an additional acceleration.

Similarly, the age of NGC 2516 (cluster 3 in Fig. 1), $\log t(\mathrm{yr}) = 8.2 \pm 0.1$ (Sung et al. 2002), is well in excess of its period of vertical oscillations through the Galactic plane, $\pi \simeq (7{-}8) \times 10^7$ yr (Dachs & Kabus 1989). NGC 2516 is presently located some 120 pc below the Galactic plane, near the dense molecular clouds of the Vela Sheet. These Galactic plane passages may have contributed to rendering the cluster unstable. Alternatively, encounters with giant molecular clouds (e.g., Gieles et al. 2006), particularly around the time of Galactic plane passages, may have contributed to the cluster's present dynamical state.

In addition, Bonatto & Bica (2003) show that tidal losses of stars from NGC 2682 to the Galactic field have been effective (see also McNamara & Sekiguchi 1986 for, e.g., NGC 2168 and NGC 2632). This interpretation is supported by the *N*-body simulations of Hurley et al. (2005). Additional (circumstantial) evidence of tidal effects acting on NGC 2682 is present in the form of significantly elliptical cluster isophotes (Fan et al. 1996), which might be a tidal extension caused by the Galactic field (Bergond et al. 2001)[8]. In addition, Chupina & Vereshchagin (1998) detected several density enhancements in the low-density extended outskirts of the cluster. Such clumps are expected as a consequence of disc shocking (e.g., Bergond et al. 2001). Alternatively, the cluster may have undergone a number of encounters with giant molecular clouds, possibly leading to a similar morphology. Similarly, Adams et al. (2001) suggest that the flattening of the stellar mass function of the Pleiades below $m_* \sim 0.2\ M_\odot$ with respect to the field-star population may have been caused by evaporation of the lowest-mass stars into the Galactic field (see also van Leeuwen 1983), although evidence that this may be the case remains inconclusive (see, e.g., the simulations of de la Fuente Marcos 2000; Moraux et al. 2004).

In a follow-up paper (Kouwenhoven et al., in prep.) we will quantitatively explore the loci in the diagnostic diagram of the Galactic open clusters, using *N*-body simulations.

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[8] NGC 3532 is also strongly flattened (Gieseking 1981), roughly orthogonal to the Galactic plane. Both theory and *N*-body simulations suggest that the effects of the Galactic tidal field give rise to a flattening of cluster outskirts in the direction towards the Galactic Centre and perpendicular to the Galactic plane (see Mathieu 1985).

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