

From Giant H II regions and H II galaxies to globular clusters and compact dwarf ellipticals.

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ABSTRACT

Massive starforming regions like Giant H II Regions (GHIIR) and H II Galaxies (HIIG) are emission line systems ionized by compact young massive star clusters (YMC) with masses ranging from $10^4 M_\odot$ to $10^8 M_\odot$.

We model the photometric and dynamical evolution over a Hubble time of the massive gravitationally bound systems that populate the tight relation between absolute blue magnitude and velocity dispersion ($M_B - \sigma$) of GHIIR and HIIG and compare the resulting relation with that one of old stellar systems: globular clusters, elliptical galaxies, bulges of spirals. After 12 Gyr of evolution their position on the σ vs. M_B plane coincides – depending on the initial mass – either with the globular clusters for systems with initial mass $M < 10^6 M_\odot$ or with a continuation of the ellipticals, bulges of spirals and ultracompact dwarfs for YMC with $M > 10^6 M_\odot$.

The slope change in the $M_B - \sigma$ and M_B -size relations at cluster masses around $10^6 M_\odot$ is due to the larger impact of the dynamical evolution on the lower mass clusters.

We interpret our result as an indication that the YMC that ionize GHIIR and HIIG can evolve to form globular clusters and ultra compact dwarf ellipticals in about 12 Gyr so that present day globular clusters and ultra compact dwarf ellipticals may have formed in conditions similar to those observed in today GHIIR and HIIG.

Key words: Giant H II regions – H II galaxies – Evolution – Globular clusters – Supersonic line widths

1 INTRODUCTION

The possible connection between young massive clusters (YMCs) and globular clusters (GCs) has been discussed in the literature mostly in relation with YMC found in the central galaxy of the Perseus cluster [NGC 1275; (Shields & Filippenko 1990; Holtzman et al. 1992)] in the central regions of interacting galaxies (Portegies Zwart et al. 2010) and in local group galaxies like the Large and Small Magellanic Clouds.

The comparable masses and sizes of YMC and GC lead to the belief that there might be an evolutionary connection

between these massive clusters posing the logical question of whether YMC could be young GC.

It is important to note that while YMC found in massive interacting galaxies and GC have comparable masses, the former (unlike GC) are metal rich and are formed in high density environments.

On the other hand, the YMC that ionize the GHIIR in dwarf irregular galaxies and in the outer regions of late spirals, have a range of masses and α -element abundances (oxygen, neon, sulphur, argon) substantially subsolar, similar to those found in GCs. In particular there have been suggestions that 30-Dor, the prototypical GHIIR in the LMC, could be a GC progenitor given its mass, size and metal content (e.g. Meylan 1993).

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Fe abundance is rarely measured in HII regions, as the ionization correction fractions for Fe can cause uncertainties of factors 2.5 - 3 depending on the degree of ionization of the region (Mónica Rodríguez, private communication) and the abundance may also be masked by depletion in dust grains (e.g. Esteban et al. 1998). In globular clusters, instead, the stellar abundances of α -elements are normally given with respect to Fe (α/Fe), and their value relative to H is then deduced from the Fe/H value.

The most extreme cases of low metallicity YMC are found in HIIG. These are YMC in dwarf galaxies that completely dominate the luminosity output having metallicities $[\text{O}/\text{H}]$ down to 1/50th of solar [see e.g. the review by Kunth & Östlin (2000)]. We have found (Chávez et al. 2014; Terlevich et al. 2015) that the properties of low- and high- z HIIG are similar in every parameter that we have measured (mass, velocity dispersion, luminosity) thus strongly suggesting that the study of low z YMC can provide important clues to the formation and evolution of GCs. A particular case is that of ID11 an actively star-forming, extremely compact galaxy and Ly α emitter at $z = 3.1$ that is gravitationally magnified by a factor of ~ 17 by the cluster of galaxies Hubble Frontier Fields AS1063. The size, luminosity, velocity dispersion and dynamical mass of ID11 resemble those of low luminosity HIIG or GHIIR such as 30 Doradus (Terlevich et al. 2016).

HIIG are narrow emission line compact starforming systems selected from spectroscopic surveys as those with the largest emission lines equivalent width (EW), e.g. $\text{EW}(\text{H}\beta) > 50\text{\AA}$ (or $\text{EW}(\text{H}\alpha) > 200\text{\AA}$) in their rest frame. The lower limit in the EW of the recombination hydrogen lines guarantees that a single and very young starburst, less than $\sim 10\text{Myr}$ in age, dominates the total luminosity output (cf. Dottori 1981; Dottori & Bica 1981; Leitherer et al. 1999; Melnick et al. 2000; Chávez et al. 2014). As a result of this selection, the possible contamination by an underlying older population or older clusters inside the spectrograph aperture as well as the ionizing photon escape are minimised. In brief, HIIG can be considered as “naked” extremely young starbursts. HIIG thus selected are spectroscopically indistinguishable from young GHIIR in nearby galaxies (e.g. 30 Doradus or NGC 604 in M33). This is underlined by the fact that when first studied in detail, the prototypical HIIGs I Zw18 and II Zw40 were dubbed “Isolated Extragalactic HII regions” (Sargent & Searle 1970).

It is interesting to note that an important fraction of GHIIR and HIIG are complex systems with one massive cluster – the youngest – dominating the luminosity¹. The possibility of these systems later merging and forming a single complex cluster is intriguing.

From the analysis of the observed distribution of EW of the Balmer lines, Terlevich et al. (2004) concluded that the evolution of HIIG is consistent with a succession of short starbursts separated by quiescent periods and that, while the emission lines trace the properties of the present dominant burst, the underlying stellar continuum traces the whole star-formation history of the galaxy. Thus, observables like the EW of the Balmer lines that combine an emission line

flux, i.e. a parameter pertaining to the present dominant burst, with the continuum flux, i.e. a parameter that traces the whole history of star formation, should not be used alone to characterize the present burst.

GHIIR have long been applied to the calibration of the extragalactic distance scale (Sandage & Tammann 1974) based on a correlation between region diameter and parent galaxy luminosity. A different approach for using GHIIR as distance indicators was proposed by Melnick (1977, 1978), who found that their diameters are well correlated with the turbulent widths of the nebular emission lines. Melnick then showed that a tighter correlation than the original one for GHIIR (diameter, parent galaxy luminosity) exists if one uses the mean turbulent velocity of the three largest HIIRs instead of their diameters. It has since been clear that GHIIR can be used as distance indicators provided an adequate high quality calibration sample is obtained.

Terlevich & Melnick (1981) found evidence from a small sample – the one available at the time – that scaling relations that apply to gravitationally bound stellar systems like elliptical galaxies, bulges of spirals and galactic globular clusters, apply also – after taking evolution into account – to HIIG and GHIIR. These are the relations between $\text{H}\beta$ luminosity, absolute blue magnitude, linear size, width of the emission lines and heavy element abundance. The underlying physics of this relation is surprisingly simple: both the luminous and mechanical power of these objects, and the gravitational potential, stem from the same source: a young massive starburst. So the physical parameter at the basis of the correlation is the total mass of the burst component. Since HIIG have a very high luminosity per unit mass, and most of their luminosity is emitted in a few strong and narrow emission lines², the spectrum of these objects is easily observable out to large redshifts ($z > 3$) with present day instrumentation.

The scatter in the $L(\text{H}\beta) - \sigma$ relation is small enough that it can be used to determine cosmic distances independently of redshift (see Melnick et al. 1988, 2000; Fuentes-Masip et al. 2000; Bosch et al. 2002; Siegel et al. 2005; Bordalo & Telles 2011; Chávez et al. 2012, 2014; Fernández Arenas et al. 2018).

The time is ripe to repeat Terlevich & Melnick (1981) analysis, using now state-of-the-art data for GC, GHIIR, HIIG and numerical models for the dynamic and stellar evolution of the clusters and such is the purpose of this work. We will assume that these systems are massive virialized star clusters, and evolve them in time. We refer to the massive ionizing stellar clusters as YMC and to the evolved non-ionizing systems as super star clusters (SSC). The paper is organized as follows: §2 introduces the data samples used; §3 presents the method to analyse the cluster evolution divided in photometric evolution, mass loss, two-body relaxation and adiabatic expansion with the consequent changes in the velocity dispersion. §4 analyses the evolution of the clusters $M_B - \sigma$ plane. Discussion and conclusions are given in §5.

¹ These ionizing clusters are much more massive than the typical HII regions in our galaxy, like e.g. Orion.

² HIIGs can reach $\text{H}\alpha$ luminosities of $10^{43} \text{ erg s}^{-1}$.

2 DATA SAMPLES

We selected from the literature the data samples to use for this exercise, as detailed below.

The globular clusters sample was obtained from Harris (2010)³ a new revision of the 1996 version of the McMaster Catalogue, containing 157 objects, with parameters that now include central velocity dispersions.

The elliptical galaxies data were obtained from Faber et al. (1989), a homogeneous and high quality photometric and spectroscopic catalogue of the nearest and brightest elliptical galaxies. Distance, central velocity dispersions, velocities relative to the cosmic rest frame and residual velocities relative to a velocity-flow model are calculated in their paper for individual galaxies and groups.

The parameters for the spiral bulges are taken from Whitmore et al. (1979) who obtained velocity dispersions at the central regions of 30 galaxies, of which 21 are spirals. Their spectra are from MacGraw-Hill Observatory using an intensified Reticon scanner.

Chilingarian et al. (2011) present an analysis of high-resolution multi-object spectroscopic data for a sample of 24 Ultra Compact Dwarf galaxies in the Fornax cluster obtained with the ESO/VLT and the Fibre Large Array Multi-element Spectrograph (FLAMES).

The compilation of “local” HIIG (our own data) is from Chávez et al. (2014) who studied a sample of 128 HIIG (C14 hereinafter) selected from the SDSS on the basis of the equivalent width of $H\beta$ ($EW(H\beta) > 50\text{\AA}$) and redshift z ($0.02 < z < 0.2$). The emission-line profiles were obtained with two different spectrographs: the High Dispersion Spectrograph (HDS) on Subaru, and the Ultraviolet and Visual Echelle Spectrograph (UVES) on the VLT; the photometric fluxes are from observations in 2m-class telescopes in Mexico: San Pedro Mártir (SPM) in Baja California and Observatorio Astronómico Guillermo Haro (OAGH) in Cananea, Sonora. In addition Bordalo & Telles (2011) published emission line widths and luminosities for 118 star forming regions in HIIG (BT11 from now on), obtaining the line widths with the Fiber-fed Extended Range Optical Spectrograph (FEROS) installed on the ESO 2.2m telescope at La Silla Observatory in Chile, and the Coudé Spectrograph at Pico dos Dias Observatory (LNA/Brazil), while the spectrophotometry was obtained with the Boller & Chivens Spectrograph on the ESO-La Silla 1.52m telescope (Kehrig et al. 2004). We have also included Melnick et al. (1988) 49 HIIG high S/N spectrophotometric data that we will refer to as M88. The GHIIR include published data from Melnick et al. (1987) plus new data obtained in the Mexican 2m class telescopes mentioned above (Fernández Arenas et al. 2018).

We also included 13 high redshift ($1.5 < z < 2.4$) HIIG obtained with MOSFIRE Keck (González-Morán et al. in preparation) and 17 intermediate- z ($z \approx 0.7$) HIIG from Hoyos et al. (2005) and Pérez et al. (2016) (hereinafter H05 and P16 respectively).

The resulting $M_B - \sigma$ relation for the young systems, where M_B was obtained using equation (1) is shown in figure 1.

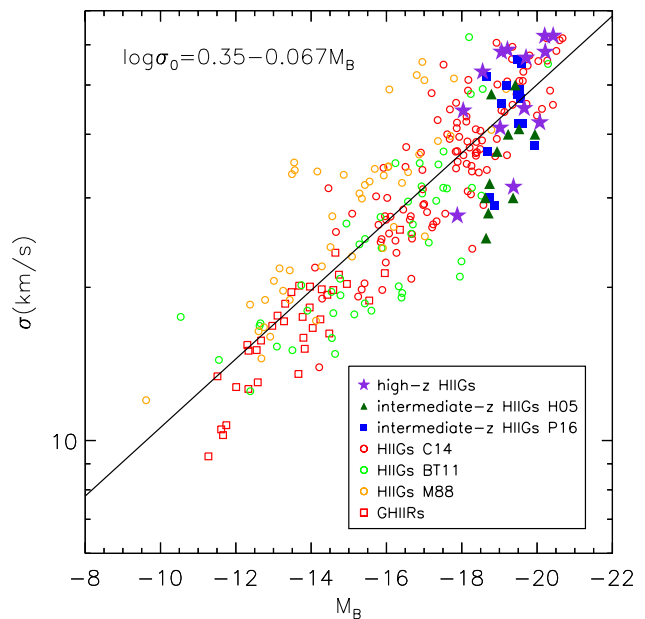


Figure 1. Correlation between the absolute magnitude in blue and the velocity dispersion for GHIIR and HIIG. The solid line represents the fit to the points, as indicated by the inset equation. The data sources are described in the text.

3 MODELLING STELLAR CLUSTER EVOLUTION

In order to compare the (M_B, σ) relation of HIIG and GHIIR with that followed by the old spheroidal stellar systems represented by globular clusters, elliptical galaxies and bulges of spiral galaxies, we have evolved the relation M_B, σ for 12 Gyr, taking into account the evolutionary changes in both magnitude and velocity dispersion as we discuss below.

All stellar systems expand as the result of stellar mass-loss. For the smaller stellar systems in this paper, i.e. masses between 10^4 and $10^6 M_\odot$ the effect of two-body relaxation results in a further expansion if the tidal field they are immersed in is relatively weak (e.g Hénon 1965; Gieles et al. 2011). It is important to bare in mind that the ionising clusters of GHIIR and HIIG are much more massive than, e.g. the more common Orion cluster and as we will show in the following sections, most of them will survive 12 Gyr of evolution without being dissolved. Gieles et al. (2010) showed that if globular clusters formed with a Faber-Jackson type relation (Faber & Jackson 1976), then the aforementioned effects would have moved the clusters with masses $\lesssim 10^6 M_\odot$ away from this original relation. The fact that globular clusters are not following now the fundamental relations of galaxies does not exclude therefore that they could have formed with the same relation.

3.1 Photometric evolution

The absolute magnitude in B (M_B) was calculated from the observed equivalent widths and $H\beta$ luminosities using equation (6) from Terlevich & Melnick (1981) modified with the

³ <http://physwww.mcmaster.ca/~harris/mwgc.dat>

new conversion from magnitudes to flux available at Gemini Observatory⁴.

$$M_B = -2.5 \log \frac{L(H\beta)}{EW(H\beta)} + 79.78 \quad (1)$$

The magnitude corrected by evolution (M_{B*}) can be expressed as:

$$M_{B*} = M_B + \Delta M_B \quad (2)$$

with the value of M_B deduced from the data and an $EW(H\beta)$ of 50\AA set to put an upper limit to the age of 5 Myrs according to instantaneous burst mode stellar population synthesis models⁵. Figure 2 (a) shows the evolution of M_B over 10^{10} yr of a *starburst99* model cluster of $10^6 M_\odot$. Evolving the magnitude up to an age of 12 Gyr, we obtain a change in M_B of $\Delta M_B = 7.3$. Changing the stellar models introduces variations of less than 0.3 magnitudes.

3.2 Stellar mass loss

When a gravitationally bound system loses mass, other parameters that characterize the system like size and velocity dispersion are modified in consequence. Various processes generate loss of mass in the object: dynamical evolution and stellar evolution (direct and induced) are the most important ones and they are protagonic on different time scales and at different stages of the evolution of the cluster (see e.g. [Lamers et al. 2010](#)). Figure 2 (b) shows the mass lost due to stellar evolution by a $10^6 M_\odot$ cluster for a specific *starburst99* model whose parameters are given below and in the figure. An example of the combined mass loss effect is shown in figure 3. One could also add the eventual loss of the remnant gas from the parental molecular cloud after the formation of the cluster. The caveat is that there is no gas in the simulations whose results we are adopting as we will see in what follows.

We have obtained the ratio to the initial mass of the mass lost by stellar evolution processes, using *starburst99* models for a cluster with total mass $10^6 M_\odot$, Padova AGB tracks with metallicity $Z=0.004$ and a Kroupa initial mass function with exponents 1.3, 2.3 and for lower, break and upper mass of 0.1, 0.5 and $100 M_\odot$ respectively. We used [Lamers et al. \(2010\)](#) models to quantify the mass loss by dynamical effects, specifically their *uf10* model, one of their largest model clusters with 83,853 M_\odot and 128,000 stars, the smallest tidal field and Roche lobe underfilling and we are assuming the loss of molecular gas to be around 10%. In table 1 we summarise the fraction of mass lost through each one of the effects just mentioned. Therefore the change in mass gives $M_f/M_i = 0.42$, and consequently the velocity dispersion using the virial theorem becomes $\sigma_f = \sigma_i \sqrt{M_f/M_i}$.

The mass loss in these systems drives an expansion, which in turn will also induce a change in the velocity dispersion. To estimate such change we use a model from [Gieles et al. \(2010\)](#) for a 12 Gyr old cluster. The change in velocity dispersion due to the expansion of the cluster is given by

⁴ Conversion from magnitudes to flux, <http://www.gemini.edu/sciops/instruments/midir-resources/imaging-calibrations/fluxmagnitude-conversion>

⁵ We have used *starburst99* ([Leitherer et al. 1999](#)).

Table 1. Lost mass fraction

ΔMass	M_{lost}/M_i
$\Delta M_{\text{evolution}}$	0.32
$\Delta M_{\text{dynamical}}$	0.16
$\Delta M_{\text{mol-gas}}$	0.10
$\Delta M_{\text{lost-total}}$	0.58

$\sigma_f = \sigma_i \sqrt{R_h/R_{h0}}$, where R_{h0}/R_h is the ratio of the initial to the final half-mass radius and σ_f and σ_i are the final and initial velocity dispersions respectively.

Finally combining the effects of mass loss and the expansion of the cluster and always assuming that these systems are virialized, the velocity dispersion becomes:

$$\sigma_f = \sigma_i \sqrt{\frac{M_f}{M_i} \frac{R_{h0}}{R_h}} \quad (3)$$

4 THE EVOLUTION OF YMC IN THE MASS- σ PLANE

In this section we describe two methods to evolve – for a Hubble time – the relation between cluster mass M and its 1D velocity dispersion σ as the result of mass loss due to the combined effect of dynamical and stellar evolution.

4.1 Analytical relations

We first consider the analytical description of the evolution with time of the half-mass radius R_h and M taken from [Gieles et al. \(2010\)](#). In this prescription the clusters are assumed to evolve in isolation (i.e. no tidal field).

4.1.1 Expansion as the result of stellar mass-loss

It is assumed that the mass decreases as the result of stellar mass loss as:

$$M(t) = M_0 \left(\frac{t}{t_*} \right)^{-\delta}, \quad t \geq t_*, \quad \delta = 0.07, \quad t_* = 2 \text{ Myr}. \quad (4)$$

where M_0 is the initial mass at the time of cluster formation. This relation gives a ratio of $M/M_0 \simeq 0.54$ at an age of 12 Gyr, which is in good agreement with most Single Stellar Population (SSP) models for a Kroupa like IMF ([Portegies Zwart et al. 2010](#)).

In the early stages of evolution clusters expand adiabatically as the result of stellar mass-loss and in this regime the radius thus evolves as (e.g. [Hills 1980](#)) :

$$R_h = R_{h0} \left(\frac{t}{t_*} \right)^\delta. \quad (5)$$

The adiabatic expansion is a slow process and gives a maximum increase of $R_h/R_{h0} \simeq 2$ after a Hubble time.

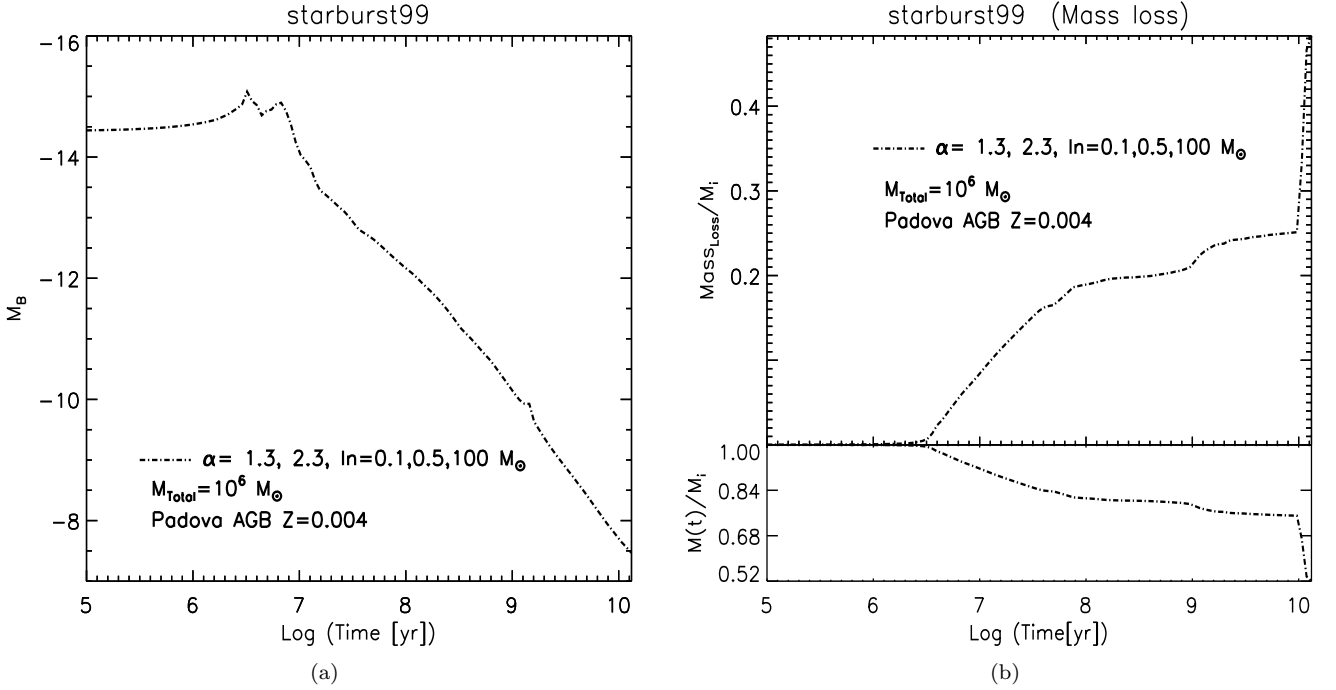


Figure 2. (a): Evolution of M_B using *starburst99* models as described in the text; (b): mass loss due to stellar evolution from *starburst99*, for a cluster with total mass $10^6 M_\odot$, Padova AGB tracks with $Z=0.004$ for a Kroupa IMF with slopes 1.3, 2.3. Fractional mass loss (mass at time t relative to the initial mass) is represented at the bottom.

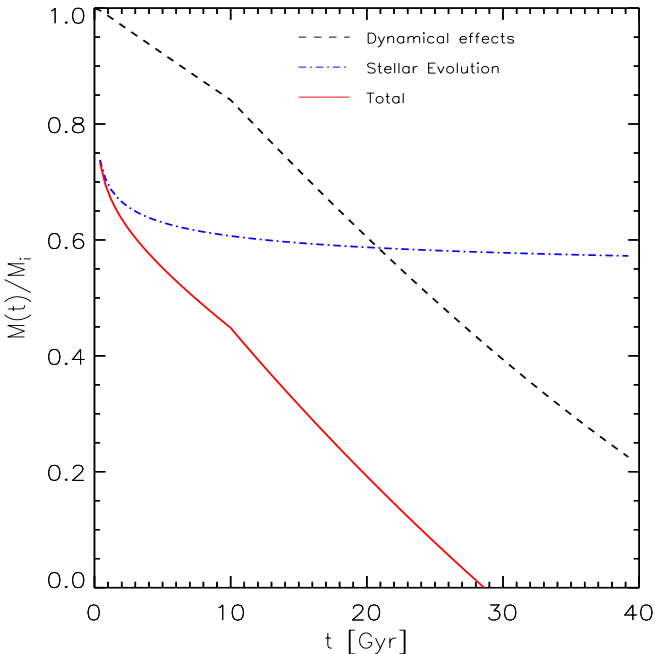


Figure 3. Change of mass due to dynamical and stellar evolution effects corresponding to model ut10 from Lamers et al. (2010).

4.1.2 Expansion as the result of two-body relaxation

Two-body relaxation becomes important when the cluster age is comparable to the half-mass relaxation time-scale T_{Rh} :

$$T_{\text{Rh}} = 0.138 \frac{N^{1/2} R_h^{3/2}}{G^{1/2} \bar{m}^{1/2} \ln \Lambda}. \quad (6)$$

where N is the number of stars in the system, G is the gravitational constant, \bar{m} is the mean stellar mass and Λ is the argument of the Coulomb logarithm that can take a value between $0.02N$ and $0.11N$ depending on the cluster mass function (Giersz & Heggie 1996).

Isolated clusters then enter a self-similar expansion phase (Hénon 1965) in which T_{Rh} grows linearly with time and $R_h \propto t^{2/3}$ (in equation 6). Gieles et al. (2010) propose a function that stitches together these two extremes in an attempt to match R_h/R_{h0} for all values of $t/T_{\text{Rh}0}$

$$R_h(t) = R_{h0} \left(\left[\frac{t}{t_*} \right]^{2\delta} + \left[\frac{\chi_t t}{T_{\text{Rh}0}} \right]^{4/3} \right)^{1/2}, \quad t \geq t_*. \quad (7)$$

where χ_t is a time-dependent term and varies because of changes of the stellar mass function, and its value at an age t is found to be well approximated by a simple power-law function

$$\chi_t \approx 3 \left(\frac{t}{t_*} \right)^{-0.3}, \quad t_* \leq t \lesssim 20 \text{ Gyr}. \quad (8)$$

If we now define $t_* \equiv \min([2 \text{ Myr}, t])$ we have a continuous

function for $R_h(T_{\text{Rh0}}, t)$, or $R_h(M_0, R_{\text{h0}}, t)$ for all t (Gieles et al. 2010).

4.1.3 Resulting σ change

We can then use the virial theorem to compute the 1D velocity dispersion as

$$\sigma(t) = \sqrt{\frac{0.4GM(t)}{3R_h(t)}} \quad (9)$$

The result of this equation is shown as a black solid line at an age of 12 Gyr in figure 5 where we show (a) the evolution of the relation between the velocity dispersion σ and the mass of the cluster and (b) the relation between the radius and the mass. The initial values are represented by the solid blue line.

4.2 EMACSS models

The analytical results of the previous section only apply to clusters evolving in isolation. To include the additional effect of a galactic tidal field, we use the fast cluster evolution code Evolve Me A Cluster of StarS (Alexander & Gieles 2012; Alexander et al. 2014, EMACSS). In this code the evolution of the cluster is treated as the flow of energy within, as a fraction of the total energy per half mass relaxation time (T_{Rh}) which can be calculated much faster than a full N -body simulation. Basically it consists of solving a series of coupled differential equations to provide the evolution of the cluster mass and radius, hence also that of the velocity dispersion.

We evolved clusters with initial masses between $3 \times 10^4 M_\odot$ and $3 \times 10^7 M_\odot$ in a tidal field with a singular isothermal halo with circular velocity of 220 km s^{-1} at galactocentric radii of $R_G = 30 \text{ kpc}$ with different initial conditions for the mass-radius relation including an initial half-mass density of $\rho_h = 10^3, 10^4, 10^5 M_\odot \text{ pc}^{-3}$. We use a Faber-Jackson initial mass-radius relation as presented by Gieles et al. (2010), and the derivation of a mass-radius relation via L - σ from Fernández Arenas et al. (2018) described in the Appendix and with $R_h = (4/3)R_{\text{eff}}$ to correct for projection as in Gieles et al. (2010).

The results of the models are shown in figure 4. It is noteworthy that the results of the initial conditions derived from the L - σ relation agree surprisingly well with the estimate of Gieles et al. (2010) based on the "de-ageing" by 10 Gyr of the observed Faber-Jackson relation and also with the Mass-Radius relation.

We also included simulations of the evolution of a cluster in a strong tidal field changing the galactocentric radius to $R_G = 3 \text{ kpc}$. The velocity dispersion was computed from M and R_h by EMACSS using equation 9.

The results are shown as filled symbols in figure 5. For clusters in a weak tidal field the result is very similar to that of the analytical estimate. For the clusters in a strong tidal field the final $M - \sigma$ relation at low masses is again that of clusters with a constant density, hence it is almost parallel to the initial relation. hasta

The main conclusion from the EMACSS evolution models is the same reached in the previous section, i.e. that the

mass lost through stellar winds and supernovae introduces a slow adiabatic expansion of the clusters that lose about 40 % of their initial mass of stars and all the remnant gas. In addition, for those systems with masses below about $10^6 M_\odot$ stellar dynamical evolution becomes important. That introduces a break in the mass-velocity dispersion relation at about $10^6 M_\odot$ (see figure 5-(a)). This break is also clearly visible in the mass-size relation as seen in the right hand side of figure 5.

5 DISCUSSION AND CONCLUSIONS

We have calculated the evolution of an individual YMC responsible for the ionization of GHIIR and HIIG as it ages over 12 Gyr. The almost identical results that we obtained using either a numerical simulation (EMACSS) or the analytical approximation, legitimises the use of the analytical expressions to estimate the evolution of the velocity dispersion from equation 3. The luminosity evolution was estimated using the results from Section 3.1.

The position on the σ vs. M_B plot of the YMC of our sample after 12 Gyr of evolution is shown in figure 6. Also plotted in the figure and specified in the inset labels, are the data from our compilation as discussed in Section 2.

We have performed fits to the evolved YMC separating the sample in two groups, those with $M < 10^6 M_\odot$ and those with $M > 10^6 M_\odot$. The resulting fits are:

$$\log \sigma = -(0.22M_B + 0.85) \quad M < 10^6 M_\odot \quad (10)$$

$$\log \sigma = -(0.11M_B - 0.04) \quad M > 10^6 M_\odot \quad (11)$$

These fittings are shown in Figure 6 as dot-dashed and dashed lines.

Haşegan et al. (2005) investigated the scaling relations for a compilation of galactic, M 31, and NGC 5128 GC, Local Group dSph, Virgo dE,N and their nuclei, Fornax Ultra Compact Dwarfs plus M 32. and elliptical galaxies. Their scaling relations converted to blue magnitudes are:

$$\log \sigma = -(0.20M_B + 0.64) \quad \text{for globular clusters} \quad (12)$$

$$\log \sigma = -(0.10M_B - 0.22) \quad \text{for elliptical galaxies} \quad (13)$$

The fittings to Haşegan et al. (2005) GC and ellipticals, the latter basically the Faber-Jackson relation, are also shown with solid lines in figure 6.

It is quite striking that the initial position of the YMC in the σ vs. M_B plane in Figure 1, shift after 12 Gyr of evolution to coincide with either the position of the globular clusters for YMC with initial mass $M < 10^6 M_\odot$ or with a continuation of the ellipticals, bulges of spirals and ultra-compact dwarfs for the more massive YMC in figure 6.

The two branches in the M_B vs. σ plot are related to the break in the mass-sigma and mass-radius relations seen in

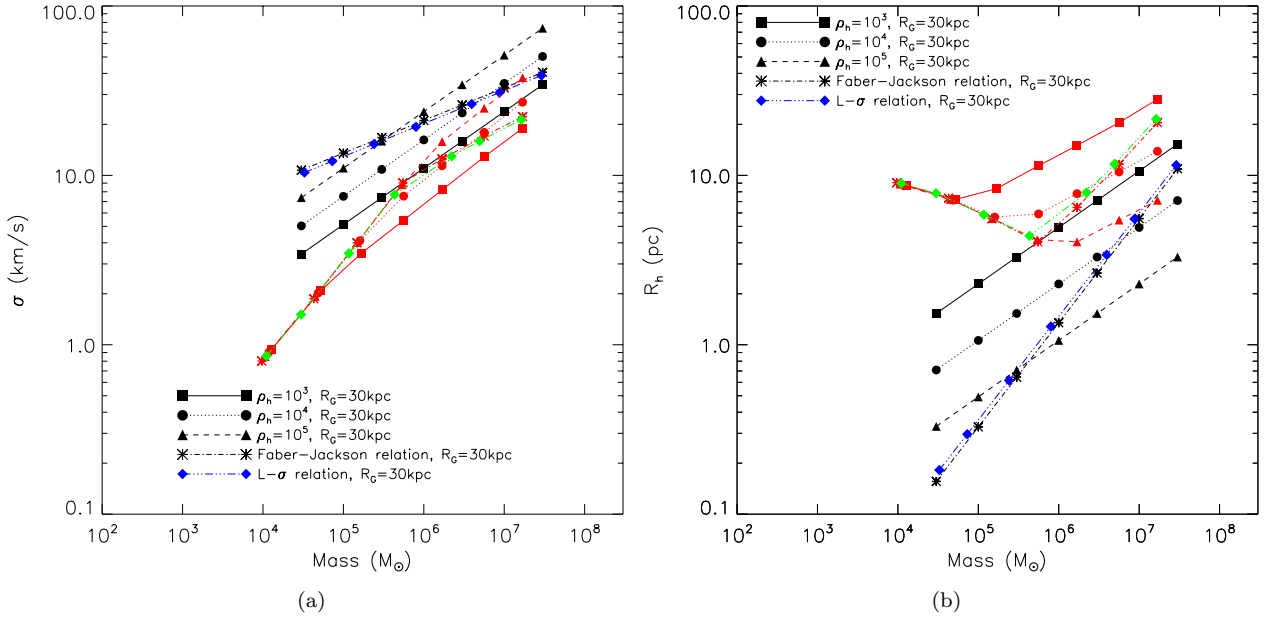


Figure 4. Evolution of the clusters (a): in the Mass- σ and (b): Mass-Radius planes for three different initial conditions in a $R_G = 30$ kpc. The black and blue points represent the initial conditions. The red and green points show the final results after 12 Gyr of evolution.

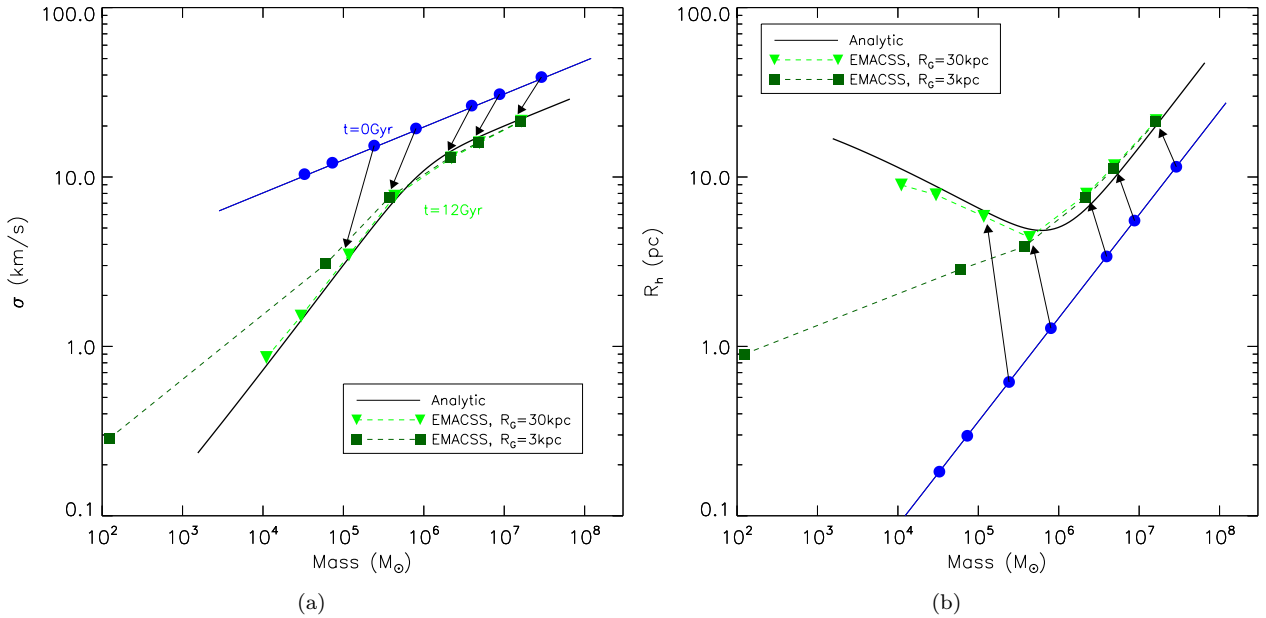


Figure 5. Evolution of the clusters in the Mass-velocity dispersion (a) and Mass-Radius (b) planes. The initial values are represented by the blue solid lines and filled circles (see Appendix A). The dashed lines show the results of the EMACSS simulations for an age of 12 Gyr (see text). Green triangles and black squares indicate a strong and weak tidal field respectively. The black solid line shows the analytical results of equations (9 and 7). The arrows join the initial and final values for each mass point.

figure 5-(a) and -(b) at about $10^6 M_{\odot}$ which manifest themselves as a change in the slope of the luminosity-sigma relation. This explains the observed different slopes in the L - σ relation of elliptical galaxies and globular clusters. This change in slope is clearly seen in the M_B vs. σ plane in figure 6, in agreement with Hasegan et al. (2005) findings, also reproduced in the figure.

The remarkable result is that not only the position of the evolved YMC in the σ vs. M_B plane coincides with the positions of GC and Ultra Compact Dwarfs but also the position of the break in the relation is reproduced and the fits to the evolved YMC are strikingly similar to those of the Hasegan et al. (2005) scaling relations for old spheroidal systems.

It is interesting to note that, our sample includes HIIG with redshifts up to 3.0 when the universe was about 2 Gyr old and probably actively forming GCs. This is in line with Elmegreen et al. (2012) suggestion that the low metallicity halo globular clusters seen in spiral galaxies (Brodie & Strader 2006) could have been formed in dwarf galaxies, in particular Ly α emitters seen as young, metal poor dwarf star-forming galaxies observed at high redshifts that are the building blocks of present day spirals.

As mentioned in the introduction, about 60% of our sample of GHIIR and HIIG show evidence of either complex morphology or definite multiplicity with one cluster, the youngest, dominating the luminosity. The possibility of these systems later merging and forming a single complex cluster is consistent with the hierarchical merger scenario for the formation of massive clusters (e.g. Krumholz & Bonnell 2007; Offner et al. 2008; Sabbi et al. 2012; Smilgys & Bonnell 2017). Terlevich et al. (2004) concluded that the evolution of HIIG is consistent with a succession of starbursts separated by short quiescent periods and that, while the emission lines trace the properties of the present dominant burst, the underlying stellar continuum traces the whole star-formation history of the galaxy. Sabbi et al. (2012) in their analysis of the stellar population in the core of the prototypical GHIIR 30 Doradus (NGC 2070) in the Large Magellanic Cloud identified two different stellar populations: the most massive and younger at the centre and a second one ~ 1 Myr older at about 5 pc away. The proximity and morphology of these clusters suggest that an ongoing merger may be occurring within the core of NGC 2070, a finding that is consistent with the predictions of models of hierarchical fragmentation of turbulent giant molecular clouds, according to which star clusters would be the final product of merging smaller sub-structures (Bonnell et al. 2003; Bate 2009; Federrath et al. 2010). Star formation will not be spread over the whole parent molecular cloud, but will be localized in gravitationally bound pockets of gas (Clark et al. 2005, 2008). Additional evidence for this scenario comes from the complexity of the structure of the other well studied GHIIR in the local group, NGC 604 in M 33 (Maíz-Apellániz et al. 2004). If GC form from mergers of smaller sub-systems, this may be related to the observed abundance anomalies and perhaps also be the reason behind the high fraction of rotating GC.

If the HII regions in our sample are indeed the progenitors of the old GCs observed in the nearby Universe, then they could potentially be used to shed light on the multiple population problem of (old) GCs. Globular clusters are characterised by light-element variations, in the form

of broadened and/or multiple main sequences, believed to be the result of star-to-star helium variations, and Na-O and Mg-Al anticorrelations (see Bastian & Lardo 2018, for a recent review). The origin of these abundance anomalies is topic of fierce debate, and various ‘polluters’ have been put forward, such as asymptotic giant branch stars (AGB stars, e.g. Ventura et al. 2001), (fast-rotating) massive stars ($\gtrsim 20 M_{\odot}$, e.g. Decressin et al. 2007; de Mink et al. 2009), and supermassive stars (SMS, $M \gtrsim 10^3 M_{\odot}$, Denissenkov & Hartwick 2014; Gieles et al. 2018). These multiple populations were once thought to be present only in the old GCs, but N spreads have recently been found in clusters as young as 2 Gyr in the Small and Large Magellanic Clouds (e.g. Martocchia et al. 2018). Measuring these abundance anomalies in the youngest massive clusters (2 Myr) is challenging and upper limits on the Al abundance in several YMCs have been established by Cabrera-Ziri et al. (2016). Small spreads in Al have been found in young ($\sim 10 - 40$ Myr) clusters in the Antennae galaxies (Lardo et al. 2017). It is therefore not clear, whether YMCs in the Local Universe form in the same way as their older counterparts. In the SMS scenario, the SMS may still be present after most of the gas has been evacuated (Gieles et al. 2018), hence the HII regions – especially those at redshift $z \sim 3$ – could be used to look for strong outflows from a SMS wind, enriched in Al, Na, and He.

In conclusion, we interpret our results as a strong indication that both young GHIIR and HIIG can evolve to form globular clusters and ultra compact dwarf ellipticals in about 12 Gyr. These results make a strong case for the detailed study of the YMC in nearby GHIIR and HIIG given that it can provide important clues to the formation and evolution of GCs.

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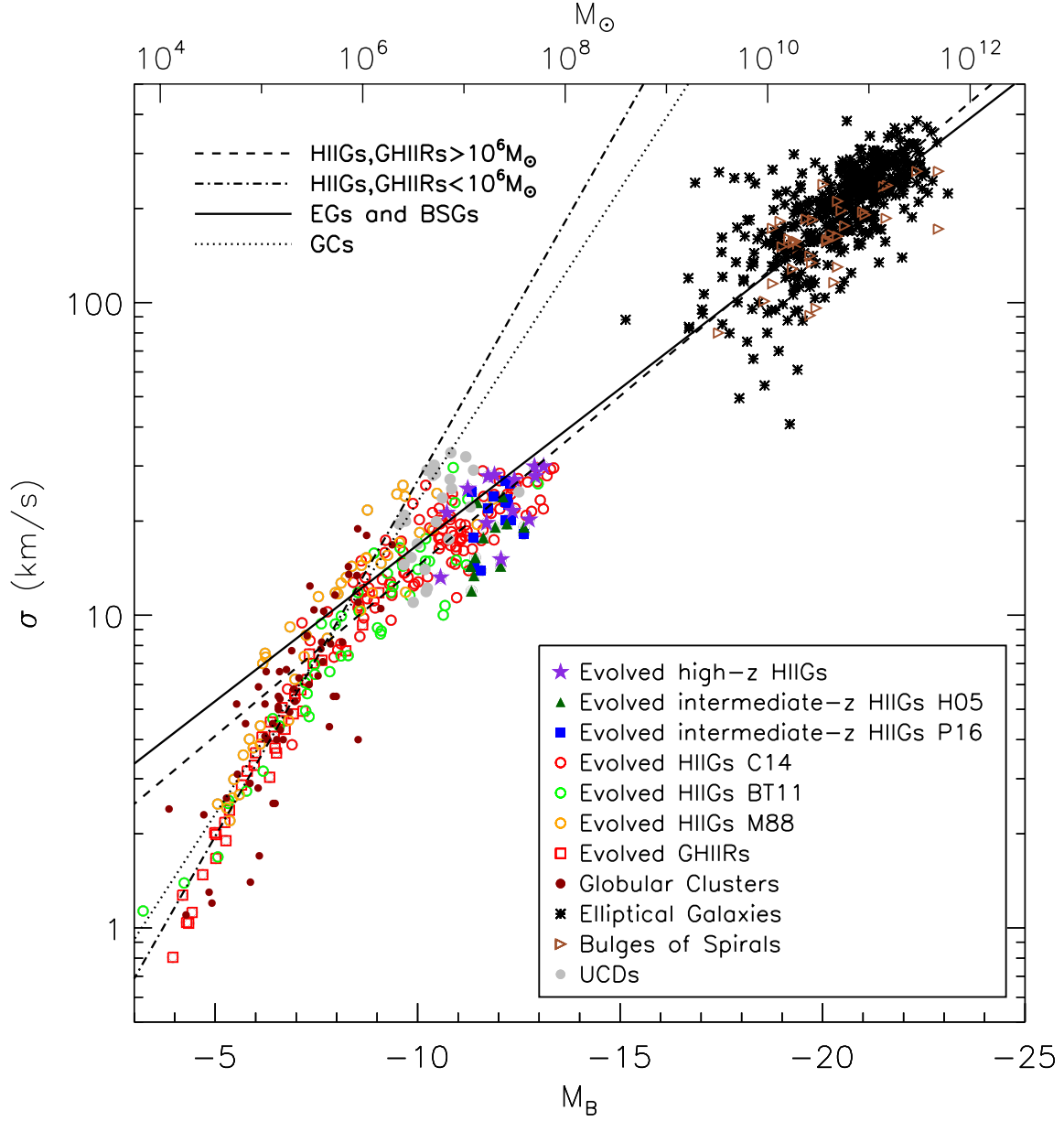


Figure 6. The position of evolved YMC is shown in the σ - M_B plane on top of the observed position of old spheroidal systems, i.e. GC, UCD, bulges of spiral galaxies (BSGs) and elliptical galaxies (EG). The solid line shows the fit to EG and BSGs while the dotted line is the fit to globular clusters given by [Hasegan et al. \(2005\)](#) (equations 12 and 13). Also shown are the fits to the evolved YMC, the dashed line for those with $M > 10^6 M_\odot$, and the dot-dashed line, for those clusters with $M < 10^6 M_\odot$ (equations (10), (11)). The upper axis labels represent the mass, estimated using an $M/L = 2$ taken from [Baumgardt \(2017\)](#).

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APPENDIX A: INITIAL CONDITIONS ESTIMATION FOR THE EVOLUTION CALCULATIONS

In the case of initial half-mass density the initial condition is computed by:

$$R_h = \left[\frac{3M_h}{8\pi\rho_h} \right]^{1/3} \quad (\text{A1})$$

We also used the observe parameters of the ionising clusters or YMC in HIIG and GHIIR to estimate the total mass and derive their size from the virial theorem. From (Fernández Arenas et al. 2018) preferred solution (N13, Table 7) corrected for evolution to the median of $EW(H\beta) = 100 \text{ \AA}$, we get:

$$\log L(H\beta) = 5.14 \log \sigma + 33.09 \quad (\text{A2})$$

From *starburst99* with Padova AGB tracks with metallicity $Z=0.004$ and a Kroupa initial mass function, a cluster that has evolved reaching $EW(H\beta) = 100 \text{ \AA}$ has:

$$\log L(H\beta) = \log(M_{tot}) + 33.73 \quad (\text{A3})$$

Using the eq. A3 we can transform the eq. A2 to mass:

$$\log L(M_{tot}) = 5.14 \log \sigma - 0.64 \text{ or } M_{tot} = 0.22\sigma^{5.14} \quad (\text{A4})$$

From the virial theorem:

$$M_{tot} = 233\eta R_{eff}\sigma^2 \quad (\text{A5})$$

Combining the eq. A5 and eq. A4 and assuming a mass profile following a King's law, we obtain:

$$R_{eff} = 9.44 \times 10^{-5} \sigma^{3.14} \quad (\text{A6})$$

The total cluster mass in equation A4 depends on assumptions about the IMF and stellar evolution tracks. The size estimate in equation A6 depends on the assumption that these YMC are virialized and follow a King's mass profile. To compare with Gieles et al. (2010) mass-radius relation, we used a $R_h = (4/3)R_{eff}$ that corrects for projection effects.

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