Gas expulsion vs gas retention: what process dominates in young massive clusters?

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ABSTRACT

The ability of young stellar clusters to expel or retain the gas left over after a first episode of star formation is a central issue in all models aiming to explain multiple stellar populations and the peculiar light element abundance patterns in globular clusters. Recent attempts to detect the gas left over from star formation in present day clusters with masses similar to those of globular clusters did not reveal a significant amount of gas in the majority of them, which strongly restricts the scenarios of multiple stellar population formation. Here the conditions required to retain the gas left over from star formation within the natal star forming cloud are revised. It is shown that the usually accepted concept regarding the thermalization of the star cluster kinetic energy due to nearby stellar winds and SNe ejecta collisions must be taken with care in the case of very compact and dense star forming clouds where three star formation regimes are possible if one considers different star formation efficiencies and mass concentrations. The three possible regimes are well separated in the half-mass radius and in the natal gas central density vs pre-stellar cloud mass parameter space. The two gas free clusters in the Antennae galaxies and the gas rich cluster with a similar mass and age in the galaxy NGC 5253 appear in different zones in these diagrams. The critical lines obtained for clusters with a solar and a primordial gas metallicity are compared.

Key words: galaxies: star clusters — Globular Clusters — Supernovae Physical Data and Processes: hydrodynamics

1 INTRODUCTION

Globular clusters (GCs), considered for a long time to be chemically homogeneous stellar systems, formed instantaneously in young assembling galaxies, are now confirmed to have a much more complex structure. Deep photometric observations and detailed spectroscopy with Hubble Space Telescope have revealed that all of them have distinct main sequence subpopulations and large star-to-star abundance variations in light elements with well documented anti-correlations between O and Na, Mg and Al (see Bedin et al. 2004; Marino et al. 2008; Carretta et al. 2009; Piotto et al. 2012; Renzini et al. 2015, and references therein). At the same time, the majority of GCs remain mono-metallic regarding the iron group elements. Only the most massive ones (e.g. ω Cen, M22, Terzan 5) exhibit multiple [Fe/H] populations which strongly restricts the ability of young proto-globular clusters to retain the iron enriched supernovae (SNe) ejecta (see Renzini 2013, and references therein). Despite many efforts to solve this problem, the discovery of multiple stellar populations in globular clusters remains one of the most challenging results of the last decade in the context of the origin and evolution of stellar populations in galaxies.

There are three main candidates that potentially reach the right hydrogen burning conditions to explain the abundance anomalies in globular clusters. These are: a) asymptotic giant branch (AGB) stars (D’Antona & Caloi 2004; D’Ercole et al. 2008); b) fast rotating massive stars (FRMS, Prantzos & Charbonnel 2006; Decressin et al. 2007; Bastian et al. 2013) and interacting massive binaries (IMB, de Mink et al. 2009; Tenorio-Tagle et al. 2016).

The applicability of the FRMS and IMB scenarios requires that young proto-globular clusters retain some of the pristine gas left over from the formation of a first stellar population for some time (20Myr-40Myr) whereas in the AGB scenario this gas is removed by stellar winds and SN explosions. The second stellar population in this latter case is formed after the end of SN explosions from the slow AGB
winds retained in the potential well of the cluster mixed with some matter accreted late in the evolution of the cluster.

Recently Bastian et al. (2013, 2014) attempted to find the matter left over from star formation in nearby young massive clusters, but did not detect any significant amount of gas (down to 1-2 per cent limits of the star cluster mass) in their target clusters. This led them to claim that even high-mass clusters with masses $10^5 M_\odot$ or more, expel their natal gas within a few Myr after their formation, which strongly restricts scenarios for multiple stellar population formation. However observations of nearby galaxies provided in infrared, millimeter and radio wavelengths revealed several very luminous and compact regions which are believed to be young stellar clusters still embedded into their natal gaseous clouds (Turner et al. 2000, 2003; Beck 2015).

1D and 3D numerical simulations provided by D’Ercole et al. (2008) and Calura et al. (2015) show that stellar winds effectively remove gas from star forming regions and completely clean them up of the pristine matter no later than 15Myr after their formation. However calculations provided by Krause et al. (2012, 2016) with a 1D thin layer approximation led to the conclusion that in most cases the expanding star cluster wind-blown shells are destroyed via Rayleigh-Taylor (RT) instabilities before reaching the escape velocity which prevents gas expulsion from the star forming region.

Another approach has been recently discussed by Tenorio-Tagle et al. (2015, 2016) who considered a model in which the negative feedback provided by stellar winds is suppressed because all massive stars compose close binary systems. The major implications of this are that the large collection of interacting massive binaries are likely to hold the remaining cloud against gravitational collapse while contaminating the gas left over from star formation. This would happen without disrupting the centrally concentrated density distribution even during the early evolution of globular clusters. Under such conditions, blast waves from sequential supernova explosions are likely to undergo blowout expelling the SN products into the ambient interstellar medium (ISM) keeping most clusters mono-metallic regarding the iron group elements.

Here we show that bubbles formed by stellar winds and single SN explosions in the central zones of compact and massive young stellar clusters may stall before merging with their neighbors. This naturally allows for the retention and enrichment of the gas left over from the formation of a 1G and likely would lead to the formation of a second generation of stars with a peculiar abundance pattern. The fate of the gas left over from star formation depends then not only on the proto-stellar cloud mass and the star formation efficiency (SFE), but also on the gas concentration (or the central gas density) in the proto-stellar cloud. The major output from our study is critical lines which separate the gas expulsion and the gas retention regimes in the star forming cloud size and in the central gas density vs star forming cloud mass parameter space and the dependence of these critical lines on the SFE.

Radiative pressure effects are presumably small in the dynamics of bubbles formed around single OB stars (Krumholz & Matzner 2009). They may be significant only for a short while in the dynamics of shells formed around star clusters (e.g. Silich & Tenorio-Tagle 2013; Martínez-González et al. 2014; Gupta et al. 2016). Such shells are driven by a high thermal pressure, which is boosted when individual stellar winds begin to collide and convert their kinetic energy into thermal energy of the injected matter. We leave the detailed analysis of radiation pressure effects on our model to a forthcoming communication.

The paper is organized as follows. In section 2 we introduce the models adopted for the initial gas and stellar density distributions in the star forming cloud and determine the rate of mechanical energy injected by massive stars into the intra-cluster medium. In this section we also discuss the dynamics of bubbles driven by individual stellar winds and individual supernova explosions and derive the conditions for them to stall before merging with their neighbors. In section 3 we split the half-mass radius vs star forming cloud mass and the central gas density vs star forming cloud mass parameter space onto three regions. In the first case, neighboring wind-driven bubbles merge and upon the collisions their shells fragment leaving the swept-up matter as a collection of dense clumps. Neighboring stellar winds begin then to interact directly causing the large overpressure that evolves into a cluster wind. The fragmented original gas will then be mass-loaded by the cluster wind and finally expelled out of the star forming volume. In the second case the wind-driven bubbles are unable to merge and are thus not able to cause the conditions for the generation of a cluster wind and the removal of the leftover gas. In this regime individual SNe may engulf neighboring wind sources. The energy input rate to the SNR then grows with time causing a continuous acceleration and eventually the SNR destruction. This immediately leads to the expelling of SN products out of the cluster. In the third region SN remnants stall before merging with nearby wind-driven bubbles. The natal gas is then contaminated with the iron group elements and retained in the central zones of the star forming cloud. Here we also discuss how the SFE and the stellar metallicity affect the critical lines which separate clusters evolving in different regimes. We also show that three clusters with similar masses and ages, two gas-less clusters in the Antennae galaxies and the gas rich cluster in the dwarf galaxy NGC 5253, are located in different regions of our half-mass radius vs star forming cloud mass diagram. Finally, in section 4 we summarize our major results and conclusions.

2 MODEL SETUP

2.1 Stellar and gas density distributions

In order to study the feedback that recently formed stars provide on their parental gaseous cloud one has to select a model for the mass density distribution in the star-forming region. Following recent works (e.g. Krause et al. 2012; Calura et al. 2015) we adopt a Plummer density distribution:

$$\rho_p(r) = \frac{3M_g}{4\pi a^2} \left(1 + \frac{a^2}{r^2}\right)^{-5/2},$$

$$n_\star(r) = \frac{3N}{4\pi a^2} \left(1 + \frac{a^2}{r^2}\right)^{-5/2},$$

where $\rho_p$ and $n_\star$ are the gas volume density and the massive star number density in the star forming cloud, respectively,
\( M_g = (1 - \epsilon M_{\text{tot}}) \) is the total amount of gas left over from the formation of the first stellar generation, \( M_{\text{tot}} \) is the total mass of the star forming cloud, \( \epsilon \) is the efficiency of star formation and \( N \) is the total number of massive stars, the major feedback agent in any young massive cluster. In the case of a Plummer density distribution the half-mass radius is \( R_{\text{hm}} = 1.3a \), where \( a \) is the characteristic length scale for the gaseous and the stellar density distributions. We assume a standard Kroupa initial mass function (IMF). The number of single massive stars \( N \) with \( M > 8 M_\odot \) then scales with the star cluster mass as (e.g. Calura et al. 2015):

\[
N = N_0 (M_*/10^4 M_\odot)^{-0.375 (9 - \gamma)} \quad (3)
\]

where \( N_0 = 10^4 \), \( M_\star = \epsilon M_{\text{tot}} \). The mean separation between nearby massive stars, \( \Delta = 2X \), is determined by the condition that within a sphere of radius \( X \) there is only one massive star: \( 4\pi X^3 n_\star / 3 = 1 \). In the case of the Plummer density distribution \( X \) grows with distance to the star cluster center:

\[
X = a \left[ 1 + \frac{a^2}{\alpha^2} \right] ^{5/6} / N^{1/3}. \quad (4)
\]

### 2.2 Input energy

Another input parameter is \( L_\star \) - the star cluster mechanical luminosity. \( L_\star \) changes in stellar populations with different metallicities and in recent starbursts is expected to be larger than it was at the epoch when the first stellar clusters (globular clusters) formed. \( L_\star \) scales with the star cluster mass as

\[
L_\star = L_0 (M_*/10^6 M_\odot), \quad (5)
\]

where the normalization coefficient \( L_0 \approx 3 \times 10^{39} \text{erg s}^{-1} \), pertaining to nearby stellar clusters with solar metallicity, standard Kroupa IMF and Padova stellar evolutionary tracks (Leitherer et al. 1999). For stellar clusters with a low metallicity, analogues to proto-globular clusters, we use the Calura et al. (2015) prescription for the stellar wind power which results in an order of magnitude smaller star cluster mechanical luminosity and thus reduces the value of the normalization coefficient \( L_0 \) to \( L_0 = 3 \times 10^{39} \text{erg s}^{-1} \). The typical power of individual stellar winds then is \( L_\star = L_*/N \). For supernovae explosions a standard value of \( 10^{51} \text{erg} \) was adopted regardless of the star formation epoch.

Note that the number of massive stars \( N \) decreases after the onset of SN explosions (it is assumed that the rate of SN explosions follows the Starburst99 model predictions). The mean separation between nearby massive stars \( \Delta \) then increases with time. Clusters which were not able to form a wind and expel the leftover gas after the first SN explosion should retain it when the separation between nearby energy sources becomes larger. Therefore hereafter we do not consider the star cluster mechanical luminosity time evolution.

The results obtained below should not be restricted to the Plummer model. For example, in the case of mass segregation (e.g. Dib et al. 2008) the assumption that the gas and massive stars are equally distributed does not hold. The mean separation between massive stars in the central zones of the cluster then would be smaller than that predicted by equation (4). This will reduce the critical radii obtained in the next sections and enhance the gas critical densities, but does not change our major conclusions.

### 2.3 Wind-driven bubbles

Each massive star composes a wind which sweeps up the surrounding medium into a shell and forms a bubble filled with a hot shocked wind gas. If thermal conduction and mass evaporation from the wind-driven shell are inhibited by magnetic fields the radiative losses of energy from the shocked wind region are negligible (Silich & Tenorio-Tagle 2013). Wind-driven bubbles then evolve in the snowplow regime and the thermal pressure inside of the wind-driven bubble decreases as the bubble grows larger (see Bisnovatyi-Kogan & Silich 1995):

\[
P = \frac{7}{25} \left( \frac{375(\gamma - 1)L_\star}{28(9\gamma - 4)\pi N} \right)^{2/3} \rho g^{1/3} \gamma^{-4/3}. \quad (6)
\]

The bubble stalls when this pressure drops to the pressure in the ambient intra-cluster medium. We assume that in the central zones of star-forming clouds the turbulent pressure dominates over the thermal one. The stalling radius is then determined by the condition that \( P = P_t \), where the turbulent pressure \( P_t = \rho g \sigma^2 \) (e.g. Smith et al. 2006). The one-dimensional velocity dispersion \( \sigma \) is

\[
\sigma = \left( \frac{GM_{\text{tot}}}{3R_{\text{hm}}} \right)^{1/2}, \quad (7)
\]

where \( G \) is the gravitational constant and \( R_{\text{hm}} \) is the half-mass radius of the star forming cloud. In the case of a spherical cluster with an isotropic velocity distribution \( \beta = 7.5 \) (Smith & Gallagher 2001).

One can calculate now where the bubble around a single massive star stalls:

\[
R_{\text{stall},w} = \left( \frac{7\beta}{25 G} \right)^{3/4} \left[ \frac{125(\gamma - 1)L_\star}{7(1.3)^3(9\gamma - 4)(1 - \epsilon)N} \right]^{1/2} \times \left( \frac{1 + r^2/a^2}{M_{\text{tot}}} \right)^{5/4} R_{\text{hm}}. \quad (8)
\]

Stellar winds do not merge if the stalling radius is smaller than 1/2 the distance between nearby sources: \( R_{\text{stall},w} < X \). This condition together with equations (4) and (8) allow one to determine how compact the parental cloud should be in order to keep newly born stars buried within the pristine gas left over from star formation:

\[
R_{\text{hm}} < \left( \frac{25G}{7\beta} \right)^{3/5} \left[ \frac{9(9\gamma - 4)(1 - \epsilon)N}{125(\gamma - 1)L_\star} \right]^{2/5} \times \frac{M_{\text{tot}}}{N^{4/15}(1 + r^2/a^2)^{1/3}}. \quad (9)
\]

\( R_{\text{hm}} \) in equation (9) is the half-mass radius of the star forming cloud and \( r \) is the size of the central zone where stellar winds do not merge. The condition that \( r = 0 \) determines then the critical half-mass radius and the critical central density in the star forming cloud:

\[
R_{\text{hm, crit}} = \left( \frac{25G}{7\beta} \right)^{3/5} \left[ \frac{9(9\gamma - 4)(1 - \epsilon)N}{125(\gamma - 1)L_\star} \right]^{2/5} \times \frac{M_{\text{tot}}}{N^{4/15}}, \quad (10)
\]

\[
\rho_{w, crit} = \frac{3M_\star}{4\pi a_{crit}^3} = \frac{3(1 - \epsilon)M_{\text{tot}}}{4\pi(R_{\text{hm, crit}}/1.3)^3}. \quad (11)
\]
If the half-mass radius of the star forming cloud is larger than $R_{hm, crit}$ and thus the central density is smaller than the critical one, stellar winds merge everywhere inside the star forming volume. Their merging results in the fragmentation of individual wind-driven shells which leads to a plethora of dense clumps around the sources and at the same time allows for the direct collision and thermalization of neighboring winds. The hot gas then rapidly streams away from the center comprising a cluster wind which can be mass-loaded with the fragmented matter (e.g. Silich et al. 2010; Rogers & Pittard 2013). Such a wind eventually cleans up the star forming volume from the natal gas and prevents a 2G formation (Calura et al. 2015). However, if the half-mass radius of the proto-cluster cloud is smaller than $R_{hm, crit}$ and thus the central density is larger than $\rho_{w, crit}$, stellar winds do not merge in the central zone of the cluster. The size of this zone $R_{cl}$ depends on the actual half-mass radius of the proto-stellar cloud and becomes larger as one considers clouds with radii smaller than $R_{hm, crit}$.

Inside the central zone with radius $r < R_{cl}$ the 1G stars contaminate the pristine gas left over after their formation with different H-burning products providing the conditions to form a polluted 2G. Note that wind-driven bubbles do not stall in the outskirts of the cloud where they instead accelerate into a sharp density gradient and then blow out into the surrounding ISM. This restricts the size of the polluted zone and results in a centrally concentrated second subpopulation.

### 2.4 Supernovae-driven bubbles

In young stellar clusters with a normal IMF stellar winds represent a dominant negative feedback mechanism only for a short while, unless the most massive stars do not explode as supernovae, but directly form black holes (see Decressin et al. 2010; Krause et al. 2012, and references therein). It is usually assumed that in massive star clusters the first supernova explodes at an age of about 3.5Myr and since then supernova explosions become the most energetic negative feedback events responsible for the gas expulsion from the recently formed clusters. In this section we discuss the impact that SNe provide on the gas which a cluster wind did not expel from the star forming region and the conditions required to form a second subpopulation enriched with the iron group elements.

If the gas density inside a star forming cloud exceeds the critical value determined by equation (11), supernova remnants (SNRs) may stall either before or after merging with nearby wind-blown bubbles. As we show in the next section, the critical densities calculated by means of equation (11) are large. In such a case the Sedov phase terminates very rapidly (Shull 1980; Wheeler et al. 1980) and supernova remnants evolve in the snow-plow regime. The thermal pressure inside the supernova remnant then drops as it grows (Pasko & Silich 1986):

$$P = \frac{3(\gamma - 1)}{4\pi} \rho_0 R_0^{3(\gamma - 1)} r^{-3\gamma},$$

where $R_0$ is the radius at which the transition to the snow-plow regime has occurred and $E_0$ is the thermal energy of the remnant at this moment. The remnant stops under this pressure drops to that in the turbulent ambient medium which leads to the SN-driven bubble stalling radius

$$R_{stall, SN} = \frac{1}{1.3}\gamma \left[ \frac{\beta(\gamma - 1) E_0 R_0^{3(\gamma - 1)}}{(1 - \epsilon) GM_{tot}} \right]^{1/3\gamma} \times \left[ 1 + \frac{r^2}{a^2} \right]^{5/6\gamma} R_{hm}^{3/4\gamma}.$$

As the SN expands into the rarefied gas left by a previous stellar wind, the initial radius $R_0$ could be approximated by the radius of the stalling wind-driven bubble: $R_0 \approx R_{stall,w}$ (Wheeler et al. 1980).

Numerical simulations (e.g. Chevalier 1974; Falle et al. 1990) show that about 1/2 of the supernova remnant thermal energy is radiated away during a short transition phase from the adiabatic to the radiative regime. Therefore it was assumed that the initial thermal energy $E_0$ is (Bisnovatyi-Kogan & Silich 1995):

$$E_0 = \frac{1}{2} \frac{\gamma + 1}{3\gamma - 1} E_{SN},$$

where $E_{SN} = 10^{51}$ erg is the supernova explosion energy. Note that in the very dense ambient medium ($n > 10^6$ cm$^{-3}$), strong radiative cooling sets in before the Sedov phase starts and the initial energy $E_0$ could be even smaller than this value (Terlevich et al. 1992).

The SN remnant stalling radii are much larger than those of wind-driven bubbles expanding into an equally dense ambient medium. This allows one to obtain the half-mass radii required for SNR to stall before merging with nearby wind-blown bubbles from the condition that $R_{stall, SN} < 2X$:

$$R_{hm} < \left( \frac{2}{N^{1/3}} \right)^{12\gamma - 1} \left( \frac{25G}{T^3} \right)^{\frac{9(\gamma - 1)}{15\gamma - 11}} \times \left[ \frac{9.1(\gamma - 4) - (1 - \epsilon) N}{125(\gamma - 1)L_\star} \right]^{\frac{6(\gamma - 1)}{(15\gamma - 11)(125(\gamma - 1)L_\star)} \times \left[ \frac{1}{1 + \frac{r^2}{a^2}} - \frac{N^{5(\gamma - 1)} G_{tot}}{(15\gamma - 11)(125(\gamma - 1)L_\star)} \right] M_{tot}.\right.$$}

The condition that $r = 0$ in equation (15) determines the critical half-mass radius and the critical central density in the star forming cloud:

$$R_{hm, SN, crit} = \left( \frac{2}{N^{1/3}} \right)^{12\gamma - 1} \left( \frac{25G}{T^3} \right)^{\frac{9(\gamma - 1)}{15\gamma - 11}} \times \left[ \frac{9.1(\gamma - 4) - (1 - \epsilon) N}{125(\gamma - 1)L_\star} \right]^{\frac{6(\gamma - 1)}{(15\gamma - 11)(125(\gamma - 1)L_\star)} \times \left[ \frac{1}{1 + \frac{r^2}{a^2}} - \frac{N^{5(\gamma - 1)} G_{tot}}{(15\gamma - 11)(125(\gamma - 1)L_\star)} \right] M_{tot}.\right.$$

$$\rho_{SN, crit} = \frac{3M_g}{4\pi R_{hm, SN, crit}^3} = \frac{3(1 - \epsilon) M_{tot}}{4\pi R_{hm, SN, crit}^3 (13)^{1.3}}.$$

SN-driven bubbles sweep up the gas left over from star formation and if they stall at the distance larger than the mean separation between nearby massive stars, the stellar winds formerly separated by the dense matter left over from star formation merge and add their energy to the thermal
energy of the hot bubble formed after a supernova explosion. A coherent shell that sweeps up the gas left over from star formation is then formed inside the cluster. The energy input rate in such a bubble grows rapidly as it overtakes neighboring wind sources. One can show (see Appendix A) that in this case the expanding shell accelerates even if it moves into a constant density ambient medium. Such an accelerating shell becomes destroyed via RT instabilities. The hot gas then finally escapes from the cloud carrying away all supernova products whereas fragments from the broken shell are likely to remain bound within a gravitational well of the cluster (Krause et al. 2012). Massive stars not affected by the SN blast wave then continue to contaminate the collection of RT clumps formed after blowout of previous SNRs as well as the rest of the gas left over after the formation of a first stellar generation.

In the central zones of even more compact and dense star forming clouds SNRs stall before merging with nearby wind-driven bubbles. Only in this case and with the help of the global turbulent pressure SNe are able to eventually enrich the pristine gas left over from the 1G formation with iron group elements. The radius of this zone, $R_{\text{crit}}$, is determined by the critical half-mass radius $R_{\text{hm,SN,crit}}$ and the actual half-mass radius of the proto-stellar cloud.

### 3 GAS EXPULSION VS GAS RETENTION IN YOUNG STELLAR CLUSTERS

As mentioned above, some models of multiple populations in globular clusters require the star cluster volume to be cleaned up whereas other require the primordial gas to be retained. In this section the critical lines which allow one to distinguish between clusters which expel or retain the gas left over from star formation are presented. Also, how these critical lines are affected by the proto-stellar gas metallicity and by the SFE are here discussed.

#### 3.1 Young clusters in present day galaxies

Figure 1 presents the critical radii, $R_{\text{hm,SN,crit}}$ and $R_{\text{hm,SN,crit}}$ (upper panels), and the critical gas central densities (lower panels) as a function of the star forming cloud mass, all assuming a solar gas metallicity. The left-hand and right-hand panels in Figure 1 correspond to different star formation efficiencies: $\epsilon = 0.3$ and $\epsilon = 0.7$, respectively. The critical radii and critical gas central densities for the wind-dominated and SN-dominated regimes are displayed by solid and dashed lines, respectively.

There are three zones in these diagrams. In clusters located above the solid line on the top panels and below the solid lines on the bottom panels, individual wind-driven bubbles merge with neighboring sources and form a collection of dense clumps in the whole star forming volume. Nearby stellar winds then begin to collide heating up the injected matter and forming a mass loaded star cluster wind which eventually cleans up the star forming cloud. Stellar winds are not able to merge in more compact and denser star forming clouds located in between the solid and dashed lines in these diagrams. However SNRs formed in such clusters engulf neighboring wind sources. They gain then more energy which results in their acceleration and eventually leads to the development of RT instabilities and the SN shell destruction. It is likely that RT clumps left over from the disrupted shells remain bound to the cluster (Krause et al. 2012) while the iron enriched gas escapes into the ambient ISM through the broken shells and does not pollute the gas available for a 2G. The fundamental difference between these two regimes is that individual SN explosions are not synchronized in time and space. They do not act coherently and have little effect on the leftover gas distribution (Tenorio-Tagle et al. 2015). On the other hand, if wind-driven bubbles merge, they do merge simultaneously in the whole star forming volume and eventually form a powerful, mass loaded star cluster wind. The coherence of energy sources is a fundamental ingredient as was already stressed by Calura et al. (2015); Sharma et al. (2014).

The most massive and compact star clusters located below the dashed lines in the top panels and above the dashed lines in the bottom panels, retain the pristine gas and some supernovae products. In this case the 2G should present an enhanced iron abundance.

The comparison of the left-hand and right-hand panels in Figure 1 shows that the regime of star formation strongly depends on the SFE of the 1G. The critical lines go down in the top panels and up in the bottom panels as the considered SFE for the 1G becomes larger. This implies that natal clouds with a large SFE must be more compact and denser compared to their counterparts with a low SFE in order to form the 2G subpopulation. Note also that the critical lines mark clouds which retain primordial gas only in a small central zone. However, the size of this zone and the amount of the retained gas available for the 2G formation grow rapidly in more compact clusters with an $R_{\text{hm}} < R_{\text{hm,SN,crit}}$.

The critical gas central densities are presented on the bottom panels. At first glance they look too large if one takes as a reference value the interstellar gas density in the Milky Way or another nearby galaxy. However, the stellar mass density in globular clusters with multiple stellar populations reaches $10^7 \, \text{M}_\odot \, \text{pc}^{-3}$ which corresponds to a number density of atoms about $n \approx 10^3 \, \text{cm}^{-3}$ (Renzini 2013). This value is comparable and in many cases even larger than the critical densities shown in Figure 1. Thus, it is likely that many young, massive and compact clusters may retain the gas left over from star formation in their central zones. This seems to be in conflict with the recent results by Bastian et al. (2013, 2014) who did not detect a significant amount of gas in many young (ages less than 20 Myr) massive (masses about $10^6 \, \text{M}_\odot$ or more) clusters located in different nearby galaxies and claimed that even high-mass clusters expel their natal gas within a few Myr after formation. Note, however, that not all nearby young massive clusters are free of gas. Probably the best example of an equally young and massive star cluster that still remains embedded within its natal cloud is a $\sim 10^6 \, \text{M}_\odot$, ~4Myr old cluster, in the dwarf galaxy NGC 5253 (see Turner et al. 2000, 2003, 2015; Beck 2015). In order to understand what determines such a profound difference between this cluster and those studied by Bastian and collaborators, we selected from the list of Bastian et al. (2014) two clusters whose ages and masses are similar to the massive cluster in NGC 5253. Following Krause et al. (2016) we transformed the half-light radii of the selected clusters into half-mass radii (see Table 1). Note that the half-mass radii may be even larger if...
one accounts for a possible mass segregation in the observed clusters. As the cluster in NGC 5253 is still embedded into a dense molecular cloud and is not visible at optical or UV wavelengths, we adopted the size of the radio supernebula detected around the cluster (see Turner et al. 2000; Beck 2015) as the maximum value for the star cluster half-mass radius and then accommodated all clusters in our diagram.

In the case of a low star formation efficiency (see the left-hand upper panel in Figure 1) T353/W38220 and NGC 5253 clusters are located in the parameter space were clusters should retain gas left over from star formation even in the supernovae-dominated regime. Even the older and less concentrated cluster Knot S is located in between the wind and the SN critical lines and thus should expel SN products, but retain the primordial gas and the dense RT clumps caused by blowout events. However in the case of a larger star formation efficiency (the right-hand upper panel in Figure 1), only NGC 5253 cluster remains in the total gas retention parameter space, while the Antennae clusters are to disperse their primordial gas during the wind-dominated stage. Therefore we suggest that the star formation efficiency in the Antennae clusters must have been large. The major difference between these three clusters, very similar in their mass and age, is then their compactness: the most compact cluster in the NGC 5253 galaxy remains embedded into its natal cloud whereas the less compact clusters in the Antennae are not. The stalling bubble model may also explain the lack of non-thermal radio emission from the NGC 5253 cluster (Beck et al. 1996; Martín-Hernández et al. 2005) because in this case shock waves vanish rapidly, the Fermi acceleration mechanism does not work and therefore high energy particles cannot survive for a long time after supernova explosions.

3.2 Young clusters in ancient low metallicity galaxies

There is a common belief that stellar winds driven by stars with a low metal abundances are less energetic than those driven by their metal rich counterparts. Taking into account this difference, one can calculate the critical half-mass radii and the critical central densities for young proto-stellar clouds with a low gas metallicity as was done in the previous section for present day young massive clusters. Critical lines calculated with a stellar wind mechanical luminosities as derived by D’Ercole et al. (2008) for stars with extremely low metal abundances, \( L_w = 3 \times 10^{39} (M_*/10^6 M_\odot) \) erg s\(^{-1}\), are shown in Figure 2.

An inspection of Figure 2 and its comparison with Figure 1 lead one to conclude that the requirements for proto-globular clusters to retain pristine gas left over from star formation are less stringent than those derived for present day massive clusters. Much less dense (about an order of magnitude) and less compact proto-globular clusters may retain gas left over after the 1G stars have formed. This is because stars with a low metal abundances have less energetic winds and their wind-driven bubbles stall without merging with their neighbors in lower density star forming clouds (compare the bottom panels in Figures 2 and 1). In this case SNRs also stall before merging with nearby stellar winds in less dense star forming clouds as they explode inside wind-driven bubbles with a smaller size. This significantly extends the window of opportunity to form a second stellar population in a low-metallicity clouds.

Clouds located below the solid lines on the top panels and above the solid lines on the bottom panels in Figures 1 and 2 are able to form multiple stellar populations. The mass ratio \( M_2/M_1 \) depends on the star formation efficiency (see Tenorio-Tagle et al. 2016) and on the cluster compactness. Proto-globular clouds form more massive 2G population when located further away from the wind-driven bubble critical line in the gas retention parameter space. However only very massive and compact clusters located below the dashed lines on the top panels and above the dashed lines in the bottom panels in Figures 1 and 2 are able to retain SN products and form stellar populations with different metallicities regarding the iron group elements.

4 CONCLUDING REMARKS

The common belief that stellar winds and SNRs in compact, young stellar clusters rapidly merge due to a small separation between nearby massive stars and expel the gas left over from star formation into the ambient ISM should be taken with care. Four major parameters (total mass, size, star formation efficiency and the natal gas metallicity) determine which one of the two processes - gas expulsion or gas retention - dominates in each star forming cloud and select one of the three possible star formation regimes:

- if the central gas density in the star forming cloud is small \( (\rho_g < \rho_{w,crit}) \), the collection of individual wind-driven bubbles merge and fragment. Neighboring stellar winds then collide, heat up the injected matter and form a powerful mass-loaded star cluster wind which eventually cleans out the cluster. In this case 2G stars are not formed unless the cluster accretes a sufficient amount of gas during the late stages of its evolution, as suggested in the AGB scenario (D’Ercole et al. 2008, 2010) for globular cluster formation;

- if the central gas density falls into the range \( \rho_{w,crit} < \rho_g < \rho_{SN,crit} \), stellar winds do not merge. However shells formed after individual supernova explosions engulf neighboring massive stars, gain their stellar wind energy, accelerate and eventually are disrupted via RT instabilities. As individual SN explosions are not synchronized in time and space, they have little effect on the gas distribution in the rest of the star forming cloud. RT clumps are likely to remain bound within the gravitational well of the cluster. This collection of clumps and the gas unused for the 1G formation are continuously contaminated by the 1G stars and likely form finally a second subpopulation. The hot, iron enriched gas however escapes from the cluster into the ambient ISM thorough the broken shells and does not pollute the 2G with products of SN explosions. All stellar subpopulations in such clusters should present the same iron group metallicity;

- if the central gas density in the proto-stellar cloud is large enough, \( \rho_g > \rho_{SN,crit} \), SN remnants in the central zones of the star forming cloud stall before merging with nearby stellar winds. Such clusters retain metals injected into the intra-cluster medium by SNe. Only in this case clusters with an [Fe/H] spread could be formed.

Clusters with the same mass, SFE and the natal gas metallicity but different mass concentrations evolve in different hydrodynamic regimes. More compact clusters retain...
Table 1. Observational parameters of the selected clusters

| Galaxy Cluster | Age (Myr) | Mass \(10^6 \, M_\odot\) | Half-mass Radius (pc) |
|---------------|----------|-----------------|---------------------|
| The Antennae  |          |                 |                     |
| T352/W38220   | 4        | 0.92            | \(4.1^{+2.5}_{-1.7}\) |
| Knot S        | 5        | 1.6             | \(13.6^{+12.5}_{-2.5}\) |
| NGC 5253      |          |                 |                     |
| Super star cluster in cloud D | 4.4  | 1.1             | \(0.5^{+0.15}_{-0.15}\) |

Figure 1. Critical radii and gas central densities for proto-stellar clouds with solar gas metallicity. The left-hand panels show how the critical half-mass radius and the central gas density change with the total mass of the proto-stellar cloud if the star formation efficiency \(\epsilon = 0.3\). The right-hand column shows the same in the case of the larger star formation efficiency \(\epsilon = 0.7\). In all panels solid and dashed lines display the critical cloud parameters derived for a stellar wind-dominated regime and after the onset of the supernovae explosions, respectively. Labeled symbols in the upper panels give the location of three selected clusters (see Table 1) with their corresponding error bars.
Figure 2. The same as in Figure 1, but calculated for proto-stellar clouds with a primordial gas metallicity $Z = 0.001 Z_\odot$.

the natal gas left over from the 1G formation whereas less compact ones expel it into the ambient interstellar medium. This justifies the presence of natal gas in the most compact super star cluster in NGC 5253 and the non-detection of gas left over from star formation in the less compact clusters T352/W38220 and Knot S, in the Antennae galaxies.

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APPENDIX A: SNRS IN STAR FORMING CLOUDS PERRVADED WITH STALLED WINDS

The hot bubble formed after a SN explosion should overlap nearby stellar winds which did not merge in the dense gas left over from 1G formation. In this case the wind energies are added to the thermal energy of the bubble. In the central zones of the cloud where the gas density is almost homogeneous, the equations describing the expansion of such a bubble and its leading shell are:

\[ M_{sh} = 4\pi \rho_0 R_s^3/3, \]

\[ \frac{d(uM_{sh})}{dt} = 4\pi PR^2, \]

\[ \frac{dE_{th}}{dt} = 4\pi \rho_s L_s R_s^3/3 - 4\pi PuR^2, \]

\[ P = (\gamma - 1) \frac{3E_{th}}{4\pi R^4}, \]

\[ u = \frac{dR}{dt}. \]

where \( \rho_s \) is the number density of the 1G massive stars, \( L_s \) is the mechanical power of a single stellar wind, \( R, M_{sh} \) and \( u \) are the radius, mass and the expansion velocity of the shell, respectively. \( P, E_{th} \) are the gas thermal pressure and energy inside the remnant, and \( \rho_s \) is the density of the gas left over from star formation in the central zones of the cloud. Combining equations (A2) and (A4) one can obtain:

\[ E_{th} = \frac{R}{3(\gamma - 1)} \left[ \frac{dM_{sh}}{dt} + M_{sh} \frac{du}{dt} \right]. \]

Substituting this equation into (A3), excluding \( P \) by means of (A2) and taking into account that in the case of a homogeneous gas distribution \( dM_{sh}/dt = 4\pi \rho_s u R^2 \), one can obtain:

\[ \frac{du}{dt} + 3\left(3\gamma - 2\right) \frac{u^3}{3\gamma + 4} R = \frac{3(\gamma - 1) n_s L_s}{3\gamma + 4}, \]

This equation has a power-law solution:

\[ R = \left[ \frac{8(\gamma - 1)n_s L_s}{3(30\gamma - 14)\rho_s} \right]^{1/2} \]

\[ u = \frac{3}{2} \left[ \frac{8(\gamma - 1)n_s L_s}{3(30\gamma - 14)\rho_s} \right]^{1/2} \]

Thus if the shell formed by a single SN overtakes neighboring wind sources, it would unavoidably accelerate and blowout even if expands into an ambient gas with a homogeneous density distribution.

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