A variation of the fraction of stars that form in bound clusters within M83

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ABSTRACT
Recent observations, as well as theoretical studies, have suggested that stellar cluster formation may depend on local and global environmental properties. In particular, the fraction of stars that form within long-lived bound clusters ($\Gamma$) may depend on environment, with indications that it may be higher in the more extreme environments of high star-formation rate density galaxies. How $\Gamma$ varies has important implications on the use of clusters to determine the star-formation histories of galaxies as well as our understanding of the star-formation process itself. Previous studies have estimated $\Gamma$ over full galaxies, making it difficult to discern the physical cause of the reported variations. Here, we use existing star cluster catalogues and HST-WFC3 V and I images of the grand design, face-on spiral galaxy M83 in order to see if and how $\Gamma$ varies within a single galaxy. We find that $\Gamma$ decreases strongly as a function of galactocentric radius, by a factor of $\sim 5$ over the inner $\sim 6$ kpc, in agreement with recent theoretical predictions and decreasing trends observed in the gas surface density of the galaxy.

Key words: galaxies: individual: M83 – Star clusters: Disruption model – Field stars: Star formation history

1 INTRODUCTION
During the past decades star clusters have been used as tools to follow the star formation histories (SFHs) of galaxies at distances where single stars are beyond instrumental resolution. But, how accurately can star cluster systems trace the real SFH of a galaxy? To understand galaxy formation and evolution it is important to understand how field stars and star clusters relate to each other. However, the (actual) amount of star formation happening in star clusters (that remain bound beyond the embedded phase) is still uncertain. If clusters will be used as tools to trace the SFH of a galaxy, it becomes of key importance to understand what fraction of star formation is happening in long-lived clusters, and whether or not this fraction is correlated with other host galaxy parameters. In this paper we will adopt the notation of Bastian (2008), and will refer to the fraction of stars that form in clusters (with $\tau \geq 10$ Myr) as $\Gamma$.

Various studies in the past decade have attempted to quantify $\Gamma$, each using slightly different techniques.

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process), the derived $\Gamma$ is in agreement with the Goddard relation (i.e. $\Gamma$ values of a few percent).

Kruijssen (2012) developed a theoretical framework to understand the fraction of star formation that happens in clusters. Here, bound clusters represent star formation that happens in the high-density tail-end of a hierarchical distribution of the interstellar medium (ISM). These high density regions attain a high star-formation efficiency, allowing young clusters to survive the expulsion of the residual gas left over from the star formation process. Based on this framework, Kruijssen (2012) recovered the $\Gamma$ vs $\Sigma_{\text{SF}}$ relation observed by Goddard et al. (2010). A key prediction of the model is that $\Gamma$ should also vary within a single galaxy.

The observed increase of $\Gamma$ in galaxies with increasing intensity of star formation suggests a strong relation with the host galaxy. Moreover, there appears to be a tight relation between giant molecular clouds (the birth sites of clusters) and galactic environment (e.g. Hughes et al. 2013; Schinnerer et al. 2013), which suggests that the formation and disruption of star clusters inside a galaxy must be linked with their ambient environment. However, there has been no study to date on whether $\Gamma$ varies within a galaxy, and if so, by how much. Using existing Hubble Space Telescope Wide Field Camera 3 (HST-WFC3) star cluster catalogues and the field stellar population of the galaxy M83, we present the first estimations of the variations of $\Gamma$ inside a galaxy.

We have combined available star cluster catalogues of M83 (Silva-Villa & Larsen 2011; Bastian et al. 2011). The sample partially covers the galaxy from north to south (see Fig. 1), which allows us to study the variations of the star and cluster populations (hence $\Gamma$) at different locations within the galaxy. Radial bins, with variable width but same amount of clusters per bin, have been used to avoid size-of-sample effects. The proximity of M83 ($D \approx 4.5$ Mpc; Thim et al. 2003) allows the study of the cluster and field stellar population with great detail.

2 DESCRIPTION OF THE DATA

2.1 Star cluster catalogues

For the present study here, we combine the cluster catalogues obtained by Silva-Villa & Larsen (2011) and Bastian et al. (2011). The addition of the catalogues from Silva-Villa & Larsen increase the area coverage. However, the areas are largely constrained by the fields-of-view of the HST-WFPC2, which in turns does not significantly improve the number of cluster to the total sample. The inclusion (or exclusion) of the Silva-Villa & Larsen catalogue does not affect the main conclusion of this work.

For a full description on the selection on clusters and their respective age/mass estimations and classification, we refer the reader to the works of Bastian et al. (2012) and Silva-Villa & Larsen (2011).

Due to the large overlap between ACS and WFC3 fields in the north of the galaxy, the catalogues were matched to avoid repetitions, after converting the ACS coordinates into the WFC3 system. For the coordinate transformation we used the task wcsctran in IRAF.

The final master catalogue contains 1354 star clusters, where 992 clusters have estimates of age and mass. The remaining 362 objects were only covered with 3-band photometry (BVI), hence estimations of ages and masses for those clusters will be unreliable due to different degeneracies (e.g., age-metallicity).

As part of a larger study (Silva-Villa et al. in prep.) we have constrained our sample as follow: Ages between 10 and $\sim 300$ Myr ($7.0 \leq \log(\tau/\text{yr}) \leq 8.5$), masses above $5 \times 10^3 \ M_\odot$, magnitudes brighter than $M_V \leq 22.5$ and clusters with galacto-centric radii equal or larger than 370 pc. The limits were chosen to avoid classification confusion for young sources (i.e. younger than 10 Myr), minimise the effects of stochasticity from the random sampling of the stellar initial mass function for low-mass clusters (i.e. larger than few times $10^3 \ M_\odot$), incompleteness for older sources (i.e. older than $\sim 300$ Myr), and to avoid the centre of the galaxy where the extinction is highly variable, causing a highly spatially dependent completeness limit. A total of 429 objects (out of the 992) passed our criteria. The majority of the clusters come from Bastian’s catalogue, due to the poor coverage at the south of the galaxy, with only a very small fraction of clusters passing our criteria. The reason for the low number of clusters in the south regions come from the small area covered by the HST-WFPC2 camera, which largely constrains the number of clusters with U-band photometry, required for deriving cluster ages and masses.

The cluster population of M83 has been widely
studied. Recently Mora et al. (2009), Chandar et al. (2010), Silva-Villa & Larsen (2011), Bastian et al. (2011), Fouesneau et al. (2012) and Bastian et al. (2012) have used HST (WFC3, ACS and WFPC2) imaging to study the cluster population of this galaxy, with some of the observed fields spatially overlapping. Chandar et al. (2010), Whitmore et al. (2011) and Fouesneau et al. (2012) studied the inner region of M83 using the same WFC3 imaging as Bastian et al. (2011, 2012). Bastian et al. made a comparison between their catalogue and the one obtained by Chandar et al. (2010) (for the region contained in both studies), and found that the main differences were due to the classification between clusters and associations, which is largely confined to young objects (<10 Myr). Above 10 Myr, the catalogues were in reasonable agreement, with only small differences. Since we limit our analysis to clusters with ages above 10 Myr (see § 3.1.1) our results are independent of the catalogue used.

2.2 Field stellar photometry

We performed point-spread function (PSF) photometry and summarize our procedures here. With a set of bona-fide stars visually selected in our images (measuring their FWHM with imexam, with typical values of ~ 2.4 pixels ~ 2.1 pc), we constructed an empirical PSF using the PSF task in DAOPHOT. The PSF stars were selected individually in each band, in order to appear bright and isolated. PSF photometry was done with DAOPHOT in IRAF. This procedure was applied in the same manner for each band (i.e. V and I).

Our PSF-fitting magnitudes were corrected to a nominal aperture radius of 0.5, following standard procedures. HST zeropoints were applied to the PSF magnitudes after applying aperture corrections. Zeropoints were taken from the HST webpage. Foreground extinctions values were taken from Nasa Extragalactic Database (NED).

3 RADIAL DISTRIBUTION

3.1 Star cluster population

After converting all coordinates from ACS/WFPC2 into the WFC3 reference system, we estimated the galactocentric radii of individual clusters. We adopted ([x0, y0]/pix) = (3692, 1928) on the WFC3 frame as the centre of the galaxy.

From the centre of the galaxy (starting at 400 pixels ~ 350 pc, i.e. avoiding the centre of the galaxy) until the location of the farthest cluster in our catalogue, we used radial bins with limits of Rpce = (372, 2153, 2700, 3652, 7155). Each one of the bins encloses a total of 107 clusters, with the exception of the outermost bin, where 108 objects are in the bin.

3.1.1 Cluster formation rate (CFR)

Our full cluster sample cover ages up to ~300 Myr, however, the field stellar population (see Sect. 3.2) is constrained to ages less than 100 Myr due to incompleteness. This provides the constraints on the age interval that can be used to estimate \( \Gamma \), and reduces further our sample to a total of 278 star clusters, with a total of \([72, 89, 56, 61]\) number of clusters per bin. For each interval we assume that we are complete in detecting clusters more massive than \( 5 \times 10^3 M_\odot \). The lower limit of the cluster studied was set to avoid problems coming from stochasticity in the initial mass function (see e.g. Fouesneau & Lanncon (2010), Silva-Villa & Larsen (2011), and references therein). The total stellar mass which has formed in clusters is obtained summing the observed mass of each cluster in a given age bin and extrapolating the missing mass in clusters less massive than \( 5 \times 10^3 M_\odot \). To determine the total mass in clusters with mass between \( 5 \times 10^3 M_\odot \) and 100 \( M_\odot \), we assume a power-law MF with index -2. In Table 1 we report the mean CFR values in each radial bin (see Goddard et al. 2010, Adamo et al. 2011).

3.2 Star formation history (SFH)

Following the methodology presented by Silva-Villa & Larsen (2010), we used the CMD method (Tosi et al. 1991) to estimate the SFH inside the galaxy. The CMD method uses the various observational uncertainties (photometric errors, distance, extinction) and theoretical isochrones to create a theoretical Hess diagrams for different modelled SFHs. The observed and theoretical Hess diagrams are then compared and the best estimate of the SFH is obtained. To obtain the SFH of M83, we assumed the photometric errors obtained in the photometric procedures above, \( A_B = 0.29 \), a distance of \( D \approx 4.5 \) Mpc (Thim et al. 2003), solar metallicity and theoretical Padova stellar evolutionary isochrones (Marigo et al. 2008) obtained from their webpage, assuming a Chabrier IMF (Chabrier 2003). The CMD method can take into account the binarity fraction and the mass ratio, but due to the lack of information on this parameter, we decided not to include binarity in our estimations. We refer the reader to Silva-Villa & Larsen (2010) for more details on the CMD method and a set of various test performed to estimate the reliability of the results.

Silva-Villa & Larsen (2011) used the CMD method in two regions of the galaxy, with similar galactocentric radii as the HST/WFC3 pointings, and estimated the SFH and star formation rates (SFR). The values presented by Silva-Villa & Larsen (2011) are constrained to ages between 10 and 100 Myr. These limits were chosen by the authors based on limits for completeness. Since the completeness limits for the WFC3 used in this work are significantly fainter than the previous ACS limits, we did not run additional completeness limits. Instead, we adopted the more conservative completeness limits based on the ACS imaging. The SFH and SFR estimates were done over the WFC3 images, using the same radial bins used for the star clusters. Due to the difference among the bands used by the HST images (i.e. F555W for the inner field and F814W for the outer field), for each bin we divided the bin in "north" and "south" sample and use the respective set of isochrones in our codes. After each subregion for each bin has an estimated SFR, we summed them, obtaining the SFR for the bin.

The results obtained for each bin are presented in Table 1.
Table 1. Radial variations of values for each bin used in this work.

| Annuli [pc] | SFR [M⊙ yr⁻¹] | CFR [M⊙ yr⁻¹] | Area [Kpc²] | ΣSFR × 10⁻³ [M⊙ yr⁻¹ Kpc⁻²] | QΓ | ΩΓ [Kms⁻¹ Kpc⁻¹] | σΓ [Kms⁻¹] | ΣΓ [M⊙ pc⁻²] | Γth0 [%] | Γobs [%] |
|-------------|---------------|---------------|-------------|-----------------|-----|-----------------|----------|-------------|--------|--------|
| 372 - 2153  | 0.36          | 0.05          | 8.76        | 41.1            | 3.1 | 90              | 25       | 75          | 37.2   | 14.7±2.3 |
| 2153 - 2700 | 0.33          | 0.03          | 3.17        | 104.1           | 2.5 | 60              | 16       | 40          | 22.3   | 10.3±3.1 |
| 2700 - 3652 | 0.34          | 0.01          | 7.02        | 48.4            | 2.4 | 50              | 14       | 30          | 18.4   | 3.8±2.8  |
| 3652 - 7155 | 0.34          | 0.01          | 26.16       | 13.0            | 2.0 | 40              | 10       | 20          | 13.5   | 4.1±2.6  |

† Values taken from Lundgren et al. (2004a,b). The values are for the mean of each bin.

4 DISCUSSION AND CONCLUSIONS

Based on the estimations obtained for the CFR and SFR (between 10-100Myr) in different locations of the galaxy, we can now investigate if, and how, Γ varies within M83 (see Table 1). This is shown in the left panel of Fig. 2. The errors associated to Γ were derived assuming a 0.3 dex uncertainty on the estimated cluster age/mass and a 0.1 dex for the SFH. There is a clear decreasing trend in the radial values of Γ from inside out over the radii covered by our observations, showing values ~ 3 times higher in the centre of the galaxy than in the outer regions.

We also investigated whether the observed decrease of Γ as a function of galactocentric distances is recovered using a different binning of the data. For this purpose, we divided the dataset using equally spaced radial bins. The new radii are located at the mean values of Re= [1.2, 2.9, 4.6, 6.3] Kpc. The estimations for the CFR were done in the same manner as for the variable binning cases, and we have assumed SFR=0.34 M⊙ yr⁻¹ for the 4 bins. We observed again a decrease of the values of Γ with increasing Re, in good agreement with our previous results (see Fig. 2). It is important to notice that the error bars are large for the outer region, which in turn, will lower the inferred Γ value in the inner region.

Using age intervals of 30 Myr (between 10 and 100 Myr), we estimated Γ values for three small age-bins inside each radial bin, as shown in Fig. 2 (left panel, green triangles). These results suggest that there is a decrease of Γ as a function not only of distance from the center of the galaxy, but also as a function of age (younger bins are on top of the older), most likely due to cluster disruption (Bastian et al. 2011, 2012).

Goddard et al. (2010) estimated the CFR, SFR, and Γ for the central region of M83 (inside 300 pc) using the cluster catalogue from Harris et al. (2003) and the Hα images from Meurer et al. (2001). The CFR is based on 45 massive clusters with ages between 3 to 10 Myr, which makes the estimation different from ours. The SFR was derived by Goddard et al. using the Hα images, assuming the transformation from Kennicutt (1998). The value obtained from Goddard et al. is shown as the filled (red) star in the left panel of Fig. 2 and follows the trend observed.

We note that we have not corrected for cluster disruption in our analysis. However, this is not expected to influence the trend observed in Fig. 2. If cluster disruption is independent of mass/environment (e.g., Whitmore et al. 2007), then all points will be affected equally, and only the absolute value will be affected, not the overall trend. If, however, cluster disruption does depend on mass/environment (e.g., Lamers et al. 2005) - and found for M83 by Bastian et al. 2012) then the inner regions of the galaxy should have a shorter disruption time than the outer regions (Krujissen et al. 2011). This will destroy more clusters in the inner region, which in turn, will lower the inferred Γ value in the inner region. Hence, correcting for mass/environment dependent disruption would only exacerbate the observed trend.

We can compare our observed values and trend with the prediction of the framework presented by Krujissen (2012). The observational values used as input to estimate Γ (using Krujissen’s IDL algorithm) were taken from Lundgren et al. (2004a,b), i.e. gas surface density (Σgas), velocity dispersion (σv), angular velocity (Ω). See Table 1. We assumed the mean galacto-centric value for each one of the bins and used equation 8 from Krujissen (2012) for the estimation of the (Toomre 1964) parameter Q. The theoretical predictions are higher than our estimations although they predict the same trend as observed. Some part of this discrepancy comes from cluster disruption between the time of cluster formation and the adopted age interval, as is suggested by the green symbols in Figure 2. Any remaining discrepancy can easily be due to uncertain parameters in the cluster formation model, such as the adopted feedback efficiency (see Sect. 7.1 of Krujissen 2012 for more details). What is important to highlight is that both theory and observations agree on the distribution, which is decreasing inside out across the galaxy at the rates observed.

In order to compare with previous results, in the right panel of Fig. 2 we show the relation between ΣSFR and Γ for the found bins discussed in the present work and previous estimates from the literature. The empirical fit from Goddard et al. (2010) as well as the fiducial model of Krujissen (2012) (dashed and dotted lines, respectively) as also shown. The large scatter between model and observations can come from different sources (e.g. age- and mass ranges, source detections, incomplete samples, etc).

The observations presented here cannot differentiate between the fraction of stars that are originally bound in clusters and early disruption or mass loss (i.e. it is possible that all stars are born in clusters and that the fraction of clusters destroyed within the first 10 Myr is dependent on environment). However, for the first time, we have shown that the fraction of star formation that happens in long-lived bound clusters is tightly related to the local properties of the host galaxy, and specifically that it decreases with galactic radius.
Figure 2. Left panel: The radial variation of $\Gamma$ within M83. The filled (red) circles show the estimates for the four radial bins studied in this work, while the filled (red) star represents the estimated values for the central region of M83 (Goddard et al. 2010). Open (blue) diamonds represent the theoretical expectations from the model of Kruijssen (2012). While the predictions are a factor of 2 – 3 too high, they predict the overall trend well. Green and purple triangles represent tests using smaller age intervals inside each bin and equal radii bins, respectively. The errors are derived assuming a 0.3 dex in the age/mass estimations and 0.1 dex in the star formation history estimations. In the case of equal radii bins, the errors are larger at larger $R_{gc}$ due to small number of clusters. Right panel: Comparison between the models and the observations for $\Sigma_{SFR}$ and $\Gamma$. Data taken from Goddard et al. (2010); Annibali et al. (2011); Adamo et al. (2011); Silva-Villa & Larsen (2011); Cook et al. (2012) as well as that presented here.

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