How similar is the stellar structure of low-mass late-type galaxies to that of early-type dwarfs?

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ABSTRACT

We analyse structural decompositions of 500 late-type galaxies (Hubble T-type \( \geq 6 \)) from the Spitzer Survey of Stellar Structure in Galaxies (S4G; Salo et al.), spanning a stellar mass range of about \( 10^7 \) to a few times \( 10^{10} \) M\(_{\odot}\). Their decomposition parameters are compared with those of the early-type dwarfs in the Virgo cluster from Janz et al. They have morphological similarities, including the fact that the fraction of simple one-component galaxies in both samples increases towards lower galaxy masses. We find that in the late-type two-component galaxies both the inner and outer structures are by a factor of two larger than those in the early-type dwarfs, for the same stellar mass of the component. While dividing the late-type galaxies to low and high density environmental bins, it is noticeable that both the inner and outer components of late types in the high local galaxy density bin are smaller, and lie closer in size to those of the early-type dwarfs. This suggests that, although structural differences between the late and early-type dwarfs are observed, environmental processes can plausibly transform their sizes sufficiently, thus linking them evolutionarily.

Key words: galaxies: structure – galaxies: dwarf – galaxies: evolution

1 INTRODUCTION

At low galaxy masses the analogue to Dressler’s (1980) morphology density relation (Binggeli et al. 1987) in clusters led to the inference that late-type galaxies are transformed to early-type dwarfs by environmental processes (e.g. Boselli & Gavazzi 2006). In recent years, the suggested processes, i.e. starvation, ram pressure stripping, and harassment (Larson et al. 1980; Lin & Faber 1983; Moore et al. 1998), and their relative importance have been actively discussed. Studies focused on various aspects: the relative contribution to the total population of early-type dwarfs systems (e.g. Boselli et al. 2008), the time of the transformation, i.e. late infall versus formation on cosmological time-scales along with cluster assembly (e.g. Boselli et al. 2008; Lisker et al. 2009), and its location, i.e. pre-processing in groups versus formation in galaxy clusters (e.g. Lisker et al. 2013; Paudel & Ree 2014).

The early and late-type dwarfs differ in two essential aspects: Their star formation activity and optical morphology. Quiescent early types are basically absent in low density environments below a mass threshold (Geha et al. 2012). Within galaxy clusters star-forming late-type dwarfs and early-type dwarfs with recent residual star formation are preferentially found in the outskirts of the cluster (Binggeli et al. 1987; Lisker et al. 2007). The same applies to disc features and disc-like kinematics in early-type dwarfs (Lisker et al. 2007; Toloba et al. 2015). These trends were used to underpin the idea of a environmentally driven transformation from late to early type.

Janz et al. (2012) applied the two-dimensional decomposition method to early-type dwarf galaxies in the Virgo cluster. Both single component Sérsic fits and more complicated multicomponent decompositions were performed, and it turned out that many of the galaxies are better modelled with the multicomponent models. Janz et al. (2014) concluded that the decompositions of those galaxies are likely to represent discs with a mass distribution more complex than a single component, but not as distinct as a separation into a bulge and a disc with clearly different physical properties. However, they were not able to do any thorough comparison to late-type galaxies of the same mass, since late-type spiral and irregular galaxies (Hubble types 6 \( \leq T \leq 10 \), i.e. Scd and later) are under-represented in typical samples of decomposition studies in the Local Universe (e.g. Graham & Worley 2008; Laurikainen et al. 2010, but see, e.g., Böker et al. 2003; Barazza et al. 2008).
Such a structural comparison is essential for addressing the question whether late-type galaxies as we observe them today can be the progenitors of early-type dwarfs, and, if this is the case, for assessing how much their structure needs to be altered during the transformation. Recent progress in the structural decomposition of low-mass galaxies (Janz et al. 2012, 2014; Salo et al. 2015) enables us to quantitatively compare the structures underlying the morphological differences between early and late-type dwarfs.

In this Letter we analyse the decompositions of near-infrared light distributions of 500 late-type galaxies (Salo et al. 2015) from the Spitzer Survey of Stellar Structure in Galaxies (S^4G; Sheth et al. 2010), and compare them to a similar data set for early-type dwarfs (Janz et al. 2014). We find both similarities and differences between these two galaxy types, and discuss processes that may bridge them.

2 SAMPLE AND DATA

The S^4G is a magnitude (B_T,corr < 15.5 mag), size (D_25 > 1′), and volume (d < 40 Mpc, using distances based on H I measurements) limited Spitzer survey of over 2300 galaxies. S^4G provides images at 3.6 and 4.5 μm, having a depth equivalent to about 1M_⊙ pc^{-2} at the average distance of the galaxy sample.\(^1\) This makes the S^4G ideal for the challenges posed by galaxies at the end of the Hubble sequence, due to the low galaxy masses and typically also irregular star-forming regions. The effective image resolution is 2′.1 full width at half-maximum (see Salo et al. 2015). The sample is particularly representative for the gas rich late-type galaxies at the faint end of the luminosity function considered here.

We use the morphological classifications from Buta et al. (2015) to select late-type galaxies with a Hubble T-type ≥ 6. The structural decompositions for these galaxies are taken from Salo et al. (2015). Only decompositions with an inclination i < 65° and flagged as high quality are further considered. The final sample contains ~500 galaxies. The S^4G decompositions employed GALFIT (Peng et al. 2010), relying on parametric fits and the statistical uncertainties of the pixels, and were evaluated with GALFIDL visualisations.\(^2\) Galaxies with multiple components were fitted using an exponential function for the outer structures (in few cases a Sérsic function), and Ferrers or Sérsic functions for the inner components (+PSF for a possible central point source). For the late-type dwarfs, we convert the 3.6 μm magnitudes in S^4G to the H-band, using an average colour calculated from S^4G and the 2MASS extended source catalogue (XSC; Jarrett et al. 2000). The converted H-band magnitude has a tight relation with the stellar masses based on the 3.6 μm magnitudes of Muñoz-Mateos et al. (2015; log M_⊙ ≈ −0.39 M_B + 1.61). The comparison sample of early-type dwarf galaxies in the Virgo cluster (Janz et al. 2014, galaxies with early-type classification in the Virgo cluster catalogue, Binggeli et al. 1985).

\(^1\) This corresponds to μ_H ≥ 25 mag arcsec^{-2} for typical stellar populations of the early-type dwarfs in the comparison sample, and is deeper than the typical Virgo dwarf images, which had total integration times so that comparable signal to noise at the half-light radius was achieved.

\(^2\) H. Salo, http://cc.oulu.fi/~hsalo/galfidl.html.

Figure 1. Histogram of brightnesses of analysed galaxies. Open bars represent all galaxies (with S^4G decomposition and an ellipticity < 1 − cos 65°), while the solid bars indicate simple galaxies (see text). The orange line shows the fraction of simple galaxies, with numerical values indicated in the right y-axis. For comparison the corresponding fraction for the early-type dwarf galaxies in the Virgo cluster (Janz et al. 2014) is displayed as a grey line.

3 ANALYSIS

We divide the decompositions of late-type galaxies into simple and multicomponent systems, in a similar manner as Janz et al. (2014) did for the early-type dwarfs: Simple galaxies are those for which a good fit is achieved with a single component, and, if necessary, a central point source.\(^3\) By multicomponent galaxies we mean systems in which two (fairly shallow) components, presumably forming part of the disc, were fitted with separate functions.

We find the fraction of simple late-type galaxies in S^4G to strongly depend on galaxy luminosity so that it increases towards fainter galaxies (Fig. 1). This luminosity dependence is remarkably similar to that previously obtained for the early-type dwarfs in the Virgo cluster (Janz et al. 2014). Next the parameters of the multiple component galaxies are compared in the two samples (Fig. 2). Unlike bulges and discs in bright spiral and lenticular galaxies (from bulge-disc structural decompositions; Laurikainen et al. 2010), the components in late-type and early-type dwarfs do not follow any tight scaling relations. They both appear to scatter more randomly. However, there is a clear difference in size between their structure components: For a given mass of a structure component, those in the late-type systems are on average twice as large as those in the early-type dwarfs. The overlap

\(^3\) For the late-type galaxies in the S^4G sample the exponential function was used for the simple galaxies, while Janz et al. (2014) used a more flexible Sérsic function. The definitions of simple galaxies are still comparable, since the simple early-type dwarfs are close to exponential as Janz et al. (2014) state. This is also confirmed by both simple galaxies showing compatible Sérsic n vs M_B distributions when using the one component Sérsic fit for the late types, which was also carried out for all galaxies in the S^4G.

MNRAS 000, 1–5 (2015)
between the early and late-type dwarfs in Fig. 2 is restricted to a relatively small number of objects.

In order to investigate whether the environmental effects could play a role in the above difference between the early and late-type dwarfs, we study the local environments of $S^*G$ galaxies as quantified by Laine et al. (2014): the XSC and the 2MASS Redshift Survey (RSC; Huchra et al. 2012) are used to calculate the projected surface number density $\Sigma_3 = \frac{3}{\pi R_3^2}$, with the projected distance $R_3$ to the third nearest neighbour galaxy in a velocity interval of $\pm 1000$ km s$^{-1}$ around the primary galaxy. We divide the sample galaxies to low and high-density environments using the median value of the local density of all $S^*G$ galaxies with this information available ($\log \Sigma_3 = 0.47$). Interestingly, the sizes of the outer components are smaller for those late-type dwarfs located in high local galaxy density environments: as much as about half of the galaxies in the high-density sub-sample have parameters similar to those of the early-type dwarfs, located in the high-density environment of the Virgo cluster.

4 DISCUSSION

4.1 Frequency of structures as function of luminosity

Here we found that the fraction of the structurally simple late-type galaxies in $S^*G$ increases with decreasing galaxy luminosity, and hence stellar mass, in a similar manner as among the early-type dwarfs in the Virgo cluster. This rise of the fraction was previously found also with profile decompositions by Gavazzi et al. (2001). This trend is also paralleled by the frequency of bars, spirals, and inner discs in early-type dwarfs, detected by Lisker et al. (2006a) using unsharp masking, which also become scarcer at lower mass.

For stellar discs the ability to form and retain substructures depends on the Toomre stability parameter (Toomre 1964). It is proportional to the random motions within the disc, for a given rotation curve, and inversely proportional to the surface mass density. The sharp decline of the fraction of bars, spiral arms, and other multicomponent structures towards lower galaxy mass inside the dwarf regime may therefore be explained by the low-mass discs being more stable. In addition to the lower surface density in low-mass discs, there is also observational evidence for them being dynamically hotter (Seth et al. 2005; Yoachim & Dalcanton 2006; Sánchez-Janssen et al. 2010). Theoretically, this may be expected from processes during their formation and internal evolution (e.g. Kauffmann et al. 2007). Likewise external processes, such as tidal interactions and interactions with hot gas (Gnedin 2003; Smith et al. 2010, 2012), can form such a trend by heating the low-mass galaxies with shallow potential wells more efficiently. Whether this qualitative explanation holds, will need further testing, since additional factors (see also Sánchez-Janssen et al. 2016) such as systematic differences in the stellar mass-to-light ratio, as well as differences in the expected dark matter content, from late to early-type dwarfs play a role.

Due to the RSC completeness limits, the availability of the environment information steeply decreases towards fainter magnitudes, with $\sim 50\%$ of the galaxies covered at $M_H \sim -19.5$ mag.

4.2 Galaxies with multiple components

A general similarity of the structural parameters between late and early-type dwarf galaxies was recently highlighted by, e.g., Meyer et al. (2014), Young et al. (2014), Mahajan et al. (2015), and Lian et al. (2015). However, here we find differences of the decomposition parameters that seem large enough to argue that a simple fading of late-type galaxies cannot account for the structures in early-type dwarfs (Fig. 2). Despite the difference in size, the decompositions of both galaxy types share the characteristic of a lack of clear scaling relations as found for those in lenticulars and early-type spirals, and their parameters are offset from the extrapolation of those relations (e.g. when plotting other galaxy types in $S^*G$ or when comparing to Laurikainen et al. 2010). The scales of bulges and discs in these systems are generally also better separated, i.e. many having bulge-to-disc scale ratios between 1:8 and 1:32, and only massive early types have bulges with scales comparable to those of their discs.

A large majority of multicomponent late-type dwarfs are systems that have elongated inner features, in $\geq 50\%$ of the galaxies a bar component was fitted. While Salo et al. (2015) warn not to rely on the naming convention of their decomposition types when identifying bars, this is a noteworthy difference when comparing to the early-type dwarfs with bar components fitted in only 14% of the galaxies. Salo et al. (2015) also point out that a low contrast between the inner and outer components in some of the galaxies did not allow fitting the bar with a separate function, even if such a bar was recognized in the visual classification by Buta et al. (2015), who identified bars in $80\%$ of galaxies at inclinations of $i < 60^\circ$. This is manifested also in a larger bar fraction in the visual classification, compared to that obtained from ellipse fitting, or while using Fourier amplitudes of density to identify bars (see Díaz-García et al. 2015). Those late-type galaxies with multiple components, comprising a disc and inner elongated structure (‘DBAR’ in Salo et al. 2015), are included in Fig. 2, but with different symbols. They do not change the conclusion of a shift between the parameter spaces occupied by late and early-type galaxies.

The bars in low-mass late type are clearly unlike bars in bright galaxies. Therefore, also the physics of the bar formation and possible destruction are expected to be different. Bars in late-type systems are not centrally concentrated (Salo et al. 2015), and lack vertically thick inner regions typically found in Milky Way mass galaxies ($\sim 50\%$ of bars), which are manifested as Boxy/Peanut/X-shaped structures and barlenses (Athanassoula et al. 2008; Laurikainen et al. 2014; see also Combes et al. 1990).

4.3 Are early-type dwarfs transformed late types?

The similarity of behaviour as a function of luminosity of the fractions of structurally simple galaxies for early and late-type galaxies could be interpreted as early-type dwarfs being compatible with being transformed late-type systems. However, we argued in Section 4.1 that this may rather be driven by changes of disc stability. Furthermore, the twice as large sizes of inner and outer components in late-type dwarfs, when compared to those of the early types, seems to argue against such a connection. Likewise, the frequency of bar components appears too distinct between the two galaxy
types. This holds irrespective of the environment, since the frequency of bar components fitted in late types does not change from low to high local galaxy density (see, however, Méndez-Abreu et al. 2012). However, the shift of the decomposition parameters of late-type (cf. also Gutiérrez et al. 2004) towards those of early-type dwarfs across the environments suggests that environmentally induced processes could sufficiently alter the decomposition parameters.

In the harassment simulations of Aguerri & González-García (2009) massive disc galaxies with bulge and disc components were transformed by several high-speed encounters with other galaxies. During this process the bulge components approximately retained their mass, but grew in size. Meanwhile the discs were truncated (see also Mastropietro et al. 2005). In the harassment simulations of Mastropietro et al. (2005) bars were tidally induced, and the final remnant was more spherical (see also Lokas et al. 2014, 2016). A more detailed suite of simulations is needed to make firm predictions for the net effect on the frequency of bars. While the disc truncation would make the outer component effectively smaller, shrinking the inner component by similar amounts seems much harder in this context, although in some cases mass transfer via bars could work in this direction. However, effective harassment comes with substantial mass loss. While this might be an option for more massive disc galaxies (although probably on longer time-scales, see Smith et al. 2015; and also Aguerri 2016 on the multicomponent aspect) this is unlikely for late-type galaxies, which have similar stellar masses as the early-type dwarfs to start with.

Ram pressure stripping (e.g. Boselli & Gavazzi 2014) on the other hand is a more gradual process. It can possibly lead to smaller sizes of both components, since it proceeds outside in. Some simulations even suggest that during the process central star formation can be enhanced (e.g. Roediger 2009). While it remains to be seen, whether the effect is large enough, the scenario is consistent with some of the early-type dwarfs in the Virgo cluster having residual star formation in their centres (Lisker et al. 2006b). Another question is whether ram pressure stripping can explain the lack of elongated structures in early-type dwarfs. For that to work, these structures would probably need to be rather artefacts of somewhat irregular star formation, which can disappear after the cessation thereof, than dynamically stable structures. A possible imprint of ram pressure stripping could be gradual changes in the stellar populations, which may be manifested in characteristic changes of the decomposition parameters as a function of wavelength.

5 SUMMARY
In order to test the hypothesis that early-type dwarfs are transformed from late-type spirals, we have analysed the structural parameters of 500 late-type galaxies (Hubble type $T \geq 6$) in the stellar mass range of about $10^7$ to a few times
$10^{10} \, M_\odot$ from the Spitzer Survey of Stellar Structure in Galaxies (S’G; Sheth et al. 2010). For the structural parameters we use the two-dimensional multicomponent decompositions from Salo et al. (2015). These decompositions are compared with those previously made in a similar manner, and also in the near-infrared, for early-type dwarfs in the Virgo cluster by Janz et al. (2014).

We found an increase of the fraction of galaxies that were well-fitted with a single component with decreasing luminosity. This trend is very similar for both early and late-type galaxies. However, it might rather be driven by factors related to galaxy mass than being a definitive sign that early-type dwarfs are transformed late-type galaxies. Moreover, the structural components in late-type systems are on average twice as large as those in early-type dwarfs, ruling out a simple fading. We discussed how harassment and ram pressure can potentially alter the structural decompositions, and identified probable observable imprints. However, more detailed simulations need to test whether transformations can yield the observed early-type decompositions parameters and which process contributes at what level. Nonetheless, the changes of late-type decomposition parameters from low to high galaxy density environments suggest that such environmentally driven processes can contribute to the population of early-type dwarfs.

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Decompositions of low-mass galaxies 5