Formation and Evolution of Galaxy Bulges
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Rejuvenation of spiral bulges

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Abstract. We seek to understand whether the stellar populations of galactic bulges show evidence of secular evolution triggered by the presence of the disc. To this end we re-analyse the sample of Proctor & Sansom (2002), deriving stellar population ages and element abundances from absorption line indices as functions of central velocity dispersion and Hubble type. In agreement with other studies in the literature, we find that bulges have relatively low luminosity weighted ages, the lowest age derived being 1.3 Gyr. Hence bulges are not generally old, but actually rejuvenated systems. We discuss evidence that this might be true also for the bulge of the Milky Way. The smallest bulges are the youngest with the lowest α/Fe ratios indicating the presence of significant star formation events involving $10-30$ per cent of their total mass in the past $1-2$ Gyr. No significant correlations of the stellar population parameters with Hubble Type are found. We show that the above relationships with σ coincide perfectly with those of early-type galaxies. At a given velocity dispersion, bulges and elliptical galaxies are indistinguishable as far as their stellar populations are concerned. These results favour an inside-out formation scenario and indicate that the discs in spiral galaxies of Hubble types Sbc and earlier cannot have a significant influence on the evolution of the stellar populations in the bulge component. The phenomenon of pseudobulge formation must be restricted to spirals of types later than Sbc.

Keywords. stars: abundances – Galaxy: abundances – globular clusters: general – galaxies: stellar content – galaxies: elliptical and lenticular, cD

1. Introduction

Pseudobulges are bulges formed out of disc material in secular processes (Kormendy 1982). They 'are not just dust features or the outer disk extending inside a classical bulge all the way to the centre', but appear to be built by nuclear star formation (Kormendy & Kennicutt (2004)). In other words, the presence of pseudobulges in spiral galaxies should be detectable in their stellar populations through fingerprints of relatively recent star formation. This seems to stand in clear contrast to the commonly accepted perception that bulges are generally old. There is strong and compelling evidence that the bulk of stellar populations in the Milky Way Bulge are old without significant amounts of recent star formation (Ferreras *et al.* 2003, Zoccali *et al.* (2003)). On the other hand, blue colours, patchy dust features, and low surface brightnesses are found predominantly in bulges of later type spirals (de Jong 1996, Peletier *et al.* 1999). Moreover, bulge colour and disc colour appear to be correlated pointing toward the presence of secular evolution processes (Wyse *et al.* 1997, Peletier *et al.* 1999, Gadotti & dos Anjos 2001). Based on these indications, Kormendy & Kennicutt (2004) conclude that stellar populations are at least consistent with the expectation that the latest type galaxies must have pseudobulges. We look into this in more detail, and search for fingerprints of recent star formation in bulges by deriving average ages and abundance ratios of bulges along the Hubble sequence (see Thomas & Davies 2006 for details).

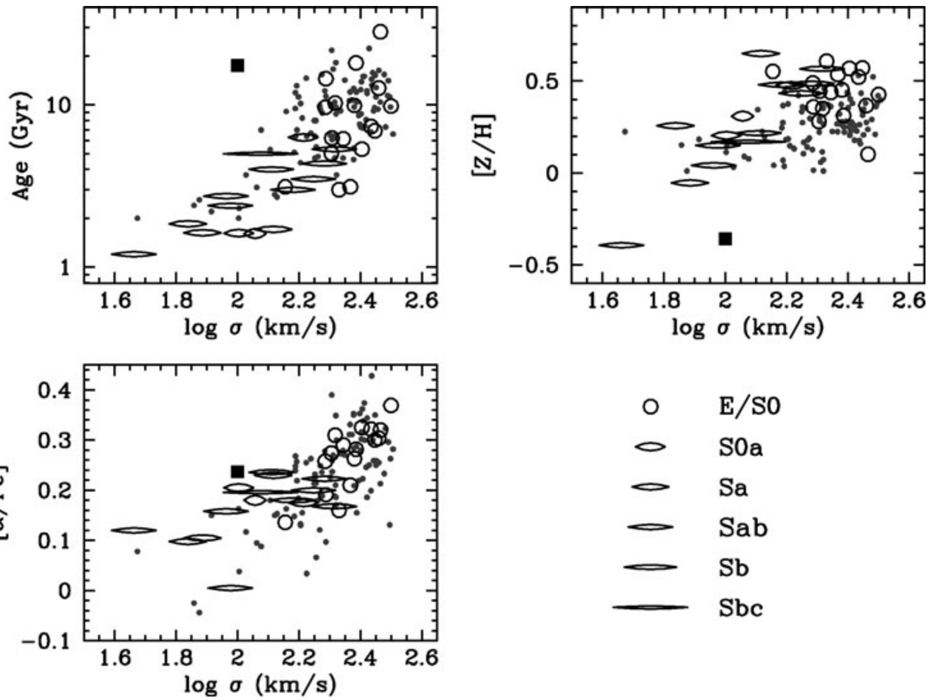

Figure 1. Stellar population parameters vs. velocity dispersion. Open circles are early-type galaxies from this work, ellipses are spiral bulges with ellipticity increasing for the later types (see labels in the right-hand bottom panel), and the filled square is the integrated light of the Milky Way Bulge. Small grey filled circles are early-type galaxies from Thomas *et al.* (2005). Central stellar populations are shown.

2. Data sample

We study the sample of Proctor & Sansom (2002; hereafter PS02) comprising 16 bulges in spirals with types Sa to Sbc, 6 lenticular and 11 elliptical galaxies. Using the stellar population models of Thomas *et al.* (2003, 2004), we derive luminosity weighted ages, metallicities, and α/Fe ratios of the central stellar populations (inner ~ 250 pc) from a combination of metal indices (Mg b, Fe5270, Fe5335) and Balmer line indices (H$\delta_{\rm A}$, H$\gamma_{\rm A}$, Hβ). The resulting stellar population parameters are compared with the results obtained by PS02, and then analysed with two-component models with the aim to quantify the possible contribution of recent star formation on the basis of a generally old population. The results are compared with the early-type galaxy sample of Thomas *et al.* (2005; hereafter T05).

3. Results

In Fig. 1 we plot age, total metallicity, and α/Fe ratio of both samples as functions of velocity dispersion. Early-type galaxies and bulges obey very similar relationships of age and α/Fe ratio with σ. Bulges seem to match well the downsizing pattern of early-type galaxies (Trager *et al.* 2000, Nelan *et al.* 2005, Thomas *et al.* 2005, Bernardi *et al.* 2006, Cappellari *et al.* 2006). Massive early-ype galaxies are old, while both low-mass early-type galaxies and spiral bulges host stellar populations with the same young luminosity weighted ages around 2–3 Gyr. In line with the young ages, they

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display relatively low α/Fe ratios of about 0.1 dex, pointing towards the presence of recent star formation. This suggests that spiral bulges and low-mass early-type galaxies are rejuvenated systems. Comparison with 2-component stellar population models shows that such rejuvenation involves about 10–30 per cent of the total mass at look-back times between $\sim$ 0.5 and 5 Gyr, corresponding to the redshift interval $0.05 \leqslant z \leqslant 0.5$.

This may indicate that secondary evolution in bulges triggered by disc instabilities as suggested by Kormendy & Kennicutt (2004) does take place, predominantly in low-mass objects. On the other hand, the stellar population properties derived in this paper do not depend on Hubble type, which complements the previous findings that disc and bulge scale lengths as well as bulge to disc ratios correlate with bulge luminosity rather than with Hubble type (Courteau *et al.* 1996, Balcells *et al.* 2007). This, in contrast, hints to an independent formation of the bulge rather than secular evolution.

Indeed, Fig. 1 suggests that bulges are generally younger than early-type galaxies, only because of their smaller masses. In other words, at a given σ, we find no difference between bulges and ellipticals, they are indistinguishable objects as far as their basic stellar population properties are concerned (in agreement with Jablonka *et al.* 1996, Wyse *et al.* 1997, Moorthy & Holtzman 2006, Jablonka *et al.* 2007). Hence, Hubble type does not determine the stellar populations of spheroids in a large range of Hubble type from E to at least Sbc, which is the latest type probed in the present study. The disc does not significantly affect the bulge's stellar populations. Hence, secular evolution and pseudobulges can only play a role in spiral galaxies with types later than Sbc.

4. The bulge of the Milky Way

The bulge of our own galaxy is known to be old. Zoccali *et al.* (2003) analyse near-IR colour magnitude diagrams of large, statistically meaningful, bulge fields. They derive an age larger than 10 Gyr and find no trace of any younger stellar population. Interestingly, this result is perfectly consistent with the luminosity weighted age that we derive in this paper from the data of Puzia *et al.* (2002) (see the square in Fig. 1). However, this old age deviates significantly from the general trend.

In the present work, the old age for our bulge is derived from the $H\delta_A$ Balmer line index, and is consistent with the age obtained from $H\beta$. However, $H\gamma_A$ suggests a considerably younger age of about 4−5 Gyr, which would then be consistent with the age-σ relationship of the other bulges. It is possible that the measurements of both $H\delta_A$ and $H\beta$ are corrupt, and that the younger age implied by $H\gamma_A$ gives the correct result. This view is supported by the similarly young age derived by Proctor *et al.* (2004) from the same data based on their χ^2 technique.

However, there is then a clear contradiction with the work of Zoccali *et al.* (2003), which might be resolved if there was a population gradient. The PS02 data and Puzia *et al.* (2002) data for the bulge sample the central region, the inner $\sim$ 250 pc, while the fields observed by Zoccali *et al.* (2003) are approximately 1 kpc from the centre. A rejuvenation of the centre of our bulge would indeed fit with the fact that young stars and star clusters are found in the very centre (Genzel *et al.* 2003). If significant, this would imply that bulges have positive age gradients, in contrast to early-type galaxies for which no age gradients are detected (Davies *et al.* 2001, Mehlert *et al.* 2003, Wu *et al.* 2005). Detailed studies of the gradients in bulges may help in future to solve this issue (Gorgas *et al.* 2007).

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5. Discussion

If central spheroids have the same properties in galaxies with and without discs, this clearly favours inside-out galaxy formation (van den Bosch 1998) according to which the disc forms after the bulge. Models that aim to explain the formation of bulges through disc fragmentation processes need to push the formation epoch to relatively high redshifts assuming high dissipation efficiencies (Immeli *et al.* 2004). Only in spiral galaxies of Hubble types later than Sbc discs can have a significant influence on the evolution of the stellar populations in the bulge component. This fits with the fact that Sersic index drops significantly in the transition between Hubble types Sbc and Sd (Balcells *et al.* 2007). Secular evolution through the disc and the phenomenon of pseudobulge formation is most likely restricted to spirals of types Sc and later.

Acknowledgements

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