Bulges of disk galaxies at intermediate redshifts: Nuclear densities and colours

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Abstract We analyze central surface brightness, nuclear and global colors of intermediate redshift disk galaxies in WFPC2/HST Groth strip and ACS/HST GOODS-N. The aim is to obtain empirical information of relative ages of bulges and disks and to study the relation among surface densities and star formation history of galaxies at $0.1 < z < 1.3$. We find that 60% of galaxies with bulges define a passive evolution red sequence, while the remaining 40% have bluer colors that may trace star formation activity. We also find that up to $z \sim 0.8$, nuclear and global $(U-B)$ colors strongly correlate with central surface brightness, in the sense that galaxies with brighter nuclei show redder colors, as found in the local Universe. This color-density scaling breaks down at $z > 0.8$, where blue colors are found in a fraction of the high-surface brightness nuclei. The associated nuclear star formation must lead to bulge growth inside disks. We argue that blue bulges in $0.8 < z < 1.3$ may be precursors of local pseudobulges. We do not find evidence for rejuvenation of classical bulges at the sampled *z*.

1 Introduction

In recent years, there has been a considerable advance in the knowledge of bulges, but many questions still remain unsolved: the relative chronology of bulges and disks (bulges formed before or after disks?), the formation mechanisms (bulges formed by mergers in the early Universe, or by secular processes in recent epochs?), the processes that quench star formation (which parameters play a role in the star formation history of bulges?). This work intend to answer some of those questions. We start giving a definition of what we understand as a bulge in our study: a *bulge* is the central excess light over the inward extrapolation of the surface brightness profile of the outer disk. In the local Universe, the bulges of spiral galaxies have

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a diverse variety of structures, star populations and dinamics. Attending to this, three types of bulges have been defined (see Athanassoula 2005 (1) and Kormendy & Kennicutt 2004 (11) for recent reviews): classical bulges, boxy-peanut shaped bulges, and pseudobulges. *Classical bulges* are dynamically hot systems whose photometry, kinematics and stellar populations resemble those of elliptical galaxies; they have red colours, high central densities, and are believed to form in a fast formation process in the early Universe, probably by major merger. *Boxy-peanut shaped bulges* are formed via the natural evolution of barred galaxies. *Pseudobulges* are believed to form through instabilities and secular processes that drive disk gas and stars from the disk to the center; they ussually have blue colours and low central densities and, star formation may still be ongoing.

2 The relative ages of bulges and disks

In this section we address the question: Are bulges older than their host disks? If we attend only to studies in the local Universe, the answer is no, since it has been found that the colours of bulges are very similar to the colour of inner regions of host disks, redder bulges live in redder disks, bulges are more similar to their parent disks than to each others (Balcells & Peletier 1994 (1), Peletier & Balcells 1996 (13)). To give a conclusive anwer to this question we need to look at higher redshifts, where the higher time resolution may allow to find differences in population ages of bulges and disks, since those epochs are closer to that of their formation.

We have studied colours of the nuclear regions of intermediate-redshift disk galaxies (see Domínguez-Palmero et al. 2008 (4), Domínguez-Palmero & Balcells 2008 (5)). We worked with an apparent-diameter limited sample of 248 galaxies from the HST Groth Strip Survey (Groth et al. 1994 (9)) and with another one of 404 objects from the HST GOODS-N field (Giavalisco et al 2004 (8)), covering redshifts $0.1 < z < 1.3$. We have found that observed nuclear colours of 60% of bulge galaxies define a red envelope with colours typical of the red sequence (see Figure 1) that fit well models of passive evolution populations of different ages. The remaining 40% have bluer colors that may trace ongoing bulge formation/growth . When comparing nuclear and host disks colours, in Figure 2, we find that they are not distinctly different: galaxies with redder bulges have redder disks; in many cases the colour differences between bulges and disks is smaller than that between bulges of different galaxies. This result that was already found for $z = 0$ galaxies is here extended up to $z = 1$. We find this correlation for any prominence of the bulge. This result may suggest an interwined star formation histories for bulges and disks.

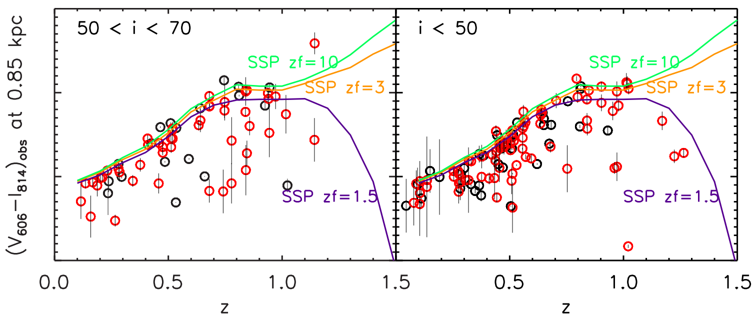

Fig. 1 Observed ($F606W - F814W$) colours measured at 0.85 kpc from the center along the minor axis vs redshift for the high- and low-inclination samples in the Groth strip and GOODS-N. *Open red circles*: nuclear colours of galaxies with prominent bulge in GOODS-N. *Open black circles*: nuclear colours of galaxies with prominent bulge in the Groth strip. *Solid lines*: observed colour tracks for passive evolution systems (SSP model with solar metallicity, a Chabrier 2003 (3) IMF, no dust) with formation redshifts equal to 10, 3 and 1.5, top to bottom.

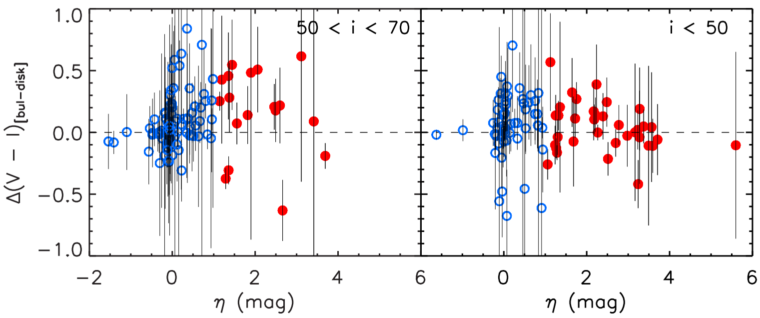

Fig. 2 Differences between bulge colour at 0.85 kpc and disk colour vs the central brightnes excess, η for the high- (left panel) and low-inclination (right panel) samples in the Groth strip. *Filled red circles*: colours of galaxies with prominent bulge. *Open blue circles*: colours of galaxies without bulges.

3 The role of surface density in star formation history of bulges

In this section, we study the role of surface density in the star formation history of bulges. For the general galaxy population in the local Universe, colour is strongly correlated with surface density, in the sense that denser galaxies are redder (Kauffmann et al. 2003 (10), Bell et al. 2000 (2)), suggesting that galaxies with high surface densities formed the bulk of their stars at earlier epochs than galaxies with lower surface densities. Focussing specifically on bulges, the relationship between colour and surface brightness may additionally provide a useful tracer of both their structure and formation mechanisms. Besides Drory & Fisher (2007) (7) argue that, in the local Universe, the three types of bulges populate different regions in colour-μ_0 diagram. So by measuring colours and central densities in distant bulges, we may be able to trace the presence of classical- boxy-peanut shaped- and pseudobulges back to $z \sim 1$. We have studied the redshift evolution of the relationship between rest-frame colours and central surface brightness, μ_0, following this purpose.

In Fig. 3, first and second rows, we plot galaxy nuclear and global rest-frame $(U-B)$ colours vs μ_0, for three redshift ranges: $z < 0.5$, $0.5 < z < 0.8$ and $0.8 < z < 1.3$ (see Domínguez-Palmero & Balcells 2009 (6)). In the range $z < 0.5$, a strong correlation exists between the $(U-B)$ rest-frame colour and μ_0, in the sense that galaxies with higher central surface brightness have redder colours, both nuclear and global, whereas those with less bright μ_0 appear bluer. The galaxies without bulges are confined to the bluer fainter region of the colour-μ_0 diagram. The trend is very strong and shows one single deviant point, a galaxy harbouring a broad-line AGN. Not only nuclear colours, but also global colours of the entire galaxy correlate to central surface density (Fig. 3d), reproducing the well established color-density trend found in the local Universe. Bluer bulges occupy the colour-μ_0 locus of star-forming galaxies, and must be forming stars. Notably, all of such galaxies, presenting lower central surface brightness than their redder counterparts, must have lower surface densities too. This observation poses a challenge to the hypothesis that such blue bulges are rejuvenated classical bulges. If they were, the high density of the underlying classical bulge, plus the high brightness of the superimposed burst, would lead to higher surface brightness than red, classical bulges, contrary to what is observed.

In the range $0.5 < z < 0.8$ the colour-μ_0 relation remains in place. Linear fits to the nuclear and to the global colour-μ_0 distributions yield very similar results to those at $z < 0.5$. However, blue deviant points are found, including both bulges and non-bulges, around $\mu_0 \sim 18.5$ and $(U-B) \sim -0.2$ (Fig. 3b). Inspection of the colour profiles of those objects shows a tendency to bluen toward the center. This may be an evidence of bulge growing at redshift $0.5 < z < 0.8$, most probably by secular processes caused by disk instabiblities or by minor satellites accretion that drive disk gas and stars to the center.

Finally, at $0.8 < z < 1.3$, while global colours strongly correlate with μ_0 like at lower redshifts (Fig. 3f), nuclear colours (Fig. 3c) show only a weak trend with μ_0. We find a population of blue, high surface brightness nuclei that was not present at lower redshifts. While some of the blue nuclei are AGN, others are not. Inspection of the colour profiles for these non-AGN galaxies reveals strongly inverted colour profiles, bluer inward, in the central ~ 2 kpc. Their blue colours and high surface brightness must trace strong episodes of star formation concentrated in the galaxy central regions.

If we attend to the evolution of the colour-μ_0 relation with the redshift, we find that the distribution becomes bluer and brighter at higher redshifts. From the least-square linear fits to the bulges plotted in the diagrams we infer that there is no a significant change in the ranges $z < 0.5$ and $0.5 < z < 0.8$, but we find that for $0.8 < z < 1.3$ the distribution keeps well below the fit to the first range, with brighter μ_0

and bluer colours. The variation in surface brightness is shown in the μ_0 histograms (Fig. 3ghi): the peak of the distributions of both disk and bulge galaxy samples (red solid and black dashed lines, respectively) displaces toward brigther μ_0 with increassing redshift. We conclude that all galaxies, with and without bulges, were brighter and bluer at $z \sim 1$ and were fading and redenning toward $z \sim 0$.

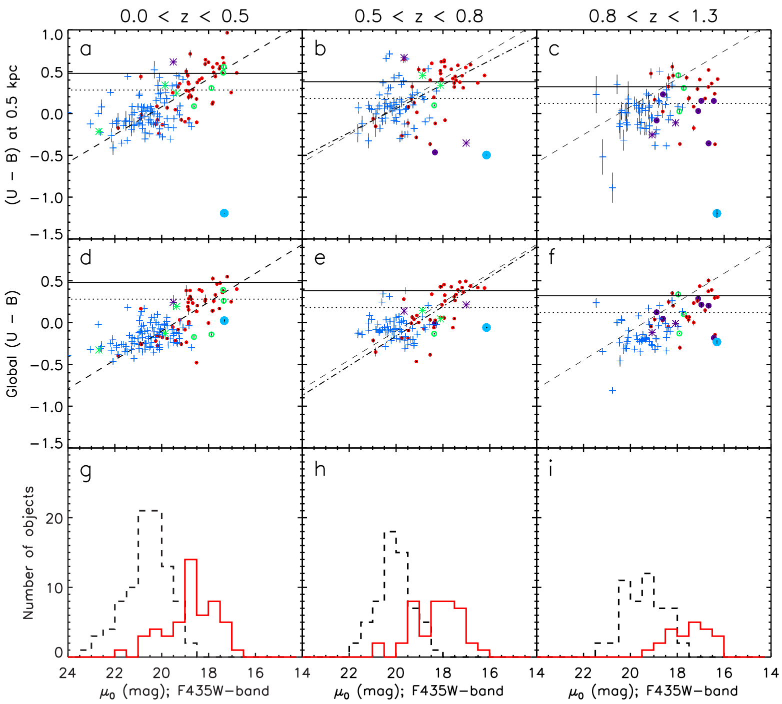

Fig. 3 **a,b,c)** and **d,e,f)** galaxy nuclear and global rest-frame $(U-B)$, respectively, vs $F435W$-band μ_0. *Small red filled circles*: normal bulge galaxies. *Intermediate green open circles*: bulge galaxies hosting a low-luminosity (LL) AGN. *Large dark blue filled circles*: bulge galaxies harbouring a narrow-line (NL) AGN. *Very large blue filled circles*: bulge galaxies hosting a broad-line (BL) AGN. *Blue crosses*: normal non-bulge galaxies. *Green asterisks*: non-bulge galaxies harbouring a LL AGN. *Blue asterisks*: non-bulge galaxies hosting a NL AGN. Colors and μ_0 errors are derived from observed errors. *Horizontal solid and dotted lines*: mean color and blue boundary of the red sequence from Kriek et al. (2008) (12). *Dashed lines*: linear least-squares fits to the color-μ_0 distribution of bulge galaxies in the $z < 0.5$ bin. *Dot-dashed lines*: least-squares fits at $0.5 < z < 0.8$ bin. **g,h,i)** $F435W$-band μ_0 histograms for the three redshifts ranges. *Solid red lines*: normal bulge galaxies. *Dashed black lines*: normal non-bulge galaxies.

4 Implication for galaxy assembly

Nuclear and global colors strongly correlate with central surface brightness (redder are brighter), hence with central surface density, extending a well known $z = 0$ behaviour up to $0.2 < z < 0.8$. Such color-μ_0 trend indicates that classical and pseudobulges exist at least up to $z \sim 1$. Classical bulges formed their stars at earlier epochs than lower density bulges.

The nuclear color-μ_0 correlation is lost at $z \gtrsim 0.8$, due to an increasing fraction of galaxies with positive nuclear color gradients (bluer inward). Nuclei bluer than the galaxy main body must correspond to episodes of strong nuclear star formation leading to bulge growth inside disk galaxies, probably by secular processes. Simple evolution models predict that such starbursting nuclei evolve into moderate surface-brightness, intermediate color $z = 0$ pseudobulges; starbursting nuclei cannot evolve into $z = 0$ classical bulges. The models also reject the possibility of rejuvenation processes for $z \sim 1$ dense and old bulges. Such dense bulges appear to have quenched star formation around 9 Gyr ago, as inferred from simple passive evolution models.

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