Stellar Populations as Building Blocks of Galaxies
Proceedings IAU Symposium No. 241, 2006
A. Vazdekis & R. F. Peletier, eds.

doi:10.1017/S174392130700912X

Colors of intermediate z bulges in Groth and GOODS-N

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Abstract. The chronology of bulge and disk formation is a major unsolved issue in galaxy formation, which impacts on our global understanding of the Hubble sequence. We present colors of the nuclear regions of intermediate-redshift disk galaxies, with the aim of obtaining empirical information of ages of bulges at $0.1 < z < 1.3$. We work with a sample of 248 galaxies (123 inclined + 125 face-on) from the HST Groth Strip Survey (Groth *et al.* 1994) and another one with 404 objects (214 inclined + 190 face-on) from the HST GOODS-N field (Giavalisco *et al.* 2004), covering redshifts $0.1 < z < 1.3$. Those samples are apparent-diameter limited at $R_{F814W} < 1.4''$, and have inclination $50° < i < 70°$ for the inclined samples and $i < 50°$ for the face-on ones. We find that, as in the Local Universe, the minor axis color profiles are negative (bluer outward), and fairly gentle, indicating that bulge colors are not distinctly different from disk colors. We apply a conservative criterion to identify bulges and potential precursors of present-day bulges, based on nuclear excess surface brightness above the exponential profile of the outer parts. For galaxies with central brightness excesses, rest-frame color distributions show a red sequence. In contrast, galaxies without central brightness excesses show typical colors of star-forming populations. Clearly, something had truncated star formation in many high-density cores, already at $z = 1$. The truncation epoch is uncertain, $1.5 < z < 10$. The color-magnitude distribution of intermediate-z bulges shows more color dispersion than that of bulges in the Local Universe. Most of bulges are as red as local bulges, while the remainder are significantly bluer, a possible sign of late bulge formation.

Keywords. Galaxies:Bulges; Galaxies:Colors; Galaxies:Ages; Galaxies Populations

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1. Selection of galaxies with measurable bulge colors and central color measurements

Selecting intermediate-redshift bulges for color measurements is difficult. Their small apparent sizes (0.13 arcsec/kpc at $z = 0.8$) and the irregular morphologies of many disk galaxies at those redshifts hamper classical bulge-disk decomposition. Besides, ideally we wish to include not only bona-fide bulges, but also likely precursors of present-day bulges. We adopt a simple surface brightness criterion to measure the prominence of the bulges above the disks. We define the bulge prominence as the excess central brightness above the inward extrapolation of an exponential fit to the outer major axis profile, measured in the most infrared band. We include in our bulge sample all those galaxies with prominence brighter than 1 mag. In this way we can ensure that all the selected galaxies have a well defined, extended bulge in which we can measure colors. Galaxies in the *no-bulge* group either have no bulges, or have an unresolved bulge. We estimated bulge colors from the color profiles derived on wedge-shaped apertures opening on the *clean* semiminor axes of the galaxies at 1.3 times the PSF of the HST images, about 0.2". This corresponds to 0.87 kpc at z = 0.3 to 1.56 kpc at z = 1.0. We also measured the colors

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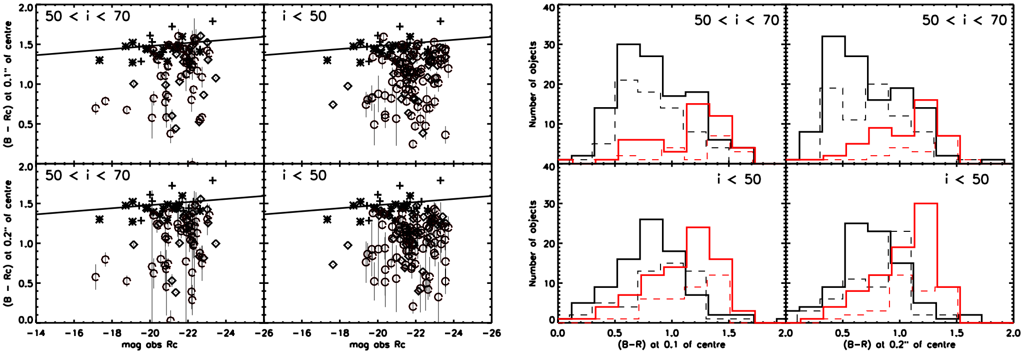

Figure 1. (**a**) Rest-frame central $(B-R)$ colors vs R-band galaxy absolute magnitude, for both samples, Groth (diamonds) and GOODS-N (circles).Crosses and asteriscs: Local Universe bulge colors with and without dust, respectively, from Peletier and Balcells (1996). Solid black line: colors-magnitude distribution of old elliptical galaxies also in Local Universe, from Schweizer and Seitzer (1992); (**b**) Histograms for $(B-R)$ color; left panels represent colors measured at 0.1" from the center and right panels the colors at 0.2". The red (or grey) lines show the color distribution of bulges and the black ones the central colors of rejected galaxies (solid lines: GOODS-N; dashed lines: Groth.

at 0.1" from the center, to compare and estimate the effect of the dust. Kcorrections for colors and magnitudes were computed using COSMOPACK (Balcells *et al.* 2003) and HyperZ v1.2 (Bolzonella *et al.* 2000).

2. Results

In **Figure 1(a)** we see that in the luminous range of local bulges, high-z bulges show a spread of colors; some are as red as local bulges, indicating that their populations have comparatively similar ages and metallicities: ages of these bulges must approach 10 Gyr. Bluer bulges probably harvest young populations, a likely indication of late bulge formation.

When representing those colors versus redshift we observe that bulge distributions have a red envelope at $(B-R) \sim 1.3-1.4$ that does not become bluer with redshift, at least until $z \sim 0.9$. We can see also, in **Figure 1(b)**, that bulge samples are dominantely redder than the non-bulge samples; as bulges have been selected only according to the central brightness excess, this would mean that it is related to redder colors. Comparing colors measured using circular apertures to those derived by taking the central color in the wedge color profile, we would clearly see that they follow the same trends. This would imply that redder bulges live in redder galaxies.

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https://doi.org/10.1017/S174392130700912X Published online by Cambridge University Press