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Bulge/Spheroid Evolution in Field and Cluster Galaxies at Redshift $z \approx 0.8$

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Abstract

We present preliminary results comparing the colors of bulges/spheroids of a sample of 52 field and 71 cluster galaxies at the same redshift $z \sim 0.8$. The photometry uses HST images and the spectral data are from Keck. We find that almost all luminous spheroids are very red, and thus presumably old, a result appearing to be independent of bulge to total ratios, disk colors, disk inclinations, and environment. Disks that host bulges are rarely redder. The half-light surface brightness of the spheroids are brighter by about one magnitude compared to spheroids today. The color-mag distributions of both cluster and field spheroids show a shallow slope, low scatter, and a red color surprisingly close to the colors of spheroids today. This lack of significant color evolution along with signficant luminosity evolution is difficult to explain by simple passive evolution after an initial brief burst. A plausible explanation includes a "drizzling" of post-burst star formation after an early burst of metal-rich star formation. We find direct support for this drizzling scenario from an observed high frequency of [OII] emission lines associated with mild star formation activity among field galaxies where both the bulges and disks are red.

1.1 Introduction

The ages of spheroids * remain an important unsolved problem in stellar populations and galaxy formation (Wyse, Gilmore, & Franx 1997). Based on studies of local galaxies and stellar populations, the three current and contending paradigms are 1) early, rapid single-collapse formation of spheroids at redshifts $z > 2$ followed by passive evolution of the stars (monolithic model); 2) formation at somewhat later epochs via merging of disk galaxies followed by disk formation from later infall of gas (merger model); and 3) very late formation equal or later than that of disks via interactions, dissipation, and evolution of a galaxy's disk or bar on time scales longer than dynamical (secular model). Because of their very different epochs for the formation of spheroids, powerful tests can be made by moving spheroid observations to redshifts $z \sim 1$ when the three scenarios predict vastly different colors and numbers of spheroids. More specifically, the monolithic picture predicts a roughly constant density of brighter, but still red spheroids to such high redshifts. In contrast, the merger picture would predict fewer spheroids at that time than today and that they would exhibit a broad range of ages and luminosities. The secular picture predicts that

* defined here to include ellipticals and the *bulges* of S0's and spirals. E, E/SO, and S0 morphological types together as a class are often called spheroidal galaxies to be designated in this paper as E-S0, to avoid the ambiguity of the E/S0 designation and confusion with spheroids

bulges are roughly the same or younger than disks at all ages while the other two scenarios would predict that spheroids are older than any associated disks.

At present, good quality data have been accessible only for luminous galaxies and spheroids at redshifts $z \sim 1$. In general, distant cluster galaxies show consistent results from different studies (a tight color-magnitude relation for E-S0 and very red colors that persist to quite high redshifts $z \sim 1$; see, e.g., van Dokkum *et al.* 2000, Blakeslee *et al.* 2003) that support the monolithic picture. With similar consistency, several studies of spiral galaxies in the field * argue against the secular model, by finding, e.g., that bulges are generally redder than disks (Abraham *et al.* 1999a; Ellis *et al.* 2001) or that bars appear to decline in number at higher redshifts (Abraham *et al.* 1999b). In contrast, field E-S0 and bulges show inconsistent and inconclusive results. For example, using the luminosity function as a number test, Lilly *et al.* (1996) find little luminosity or density evolution for red galaxies; Im *et al.* (2002) see significant luminosity evolution and little volume density evolution of morphologically selected E-S0 to $z \sim 1$; and Bell *et al.* (2004) find luminosity evolution and density evolution of red galaxies that preserve a constant luminosity density with lookback time to $z \sim 1$. Using colors as a poor-person's substitute for estimated ages, some studies support the merger picture by finding a large fraction of blue field spheroids or spheroidals at intermediate redshifts (e.g., Kodama, Bower, & Bell 1998; Abraham *et al.* 1999a; Schade *et al.* 1999; Menanteau *et al.* 2001; Ellis, Abraham, & Dickinson 2001), but the last study claims that, contrary to merger pictures, field spiral bulges at redshift $z < 0.6$ are bluer in the optical than field ellipticals. Yet this same study finds that in the near-IR, bulges at higher redshifts of $z > 0.6$ are as red or redder than the reddest ellipticals. They suggest that perhaps secular processes induce secondary star formation at redshifts $z \sim 0.6$ to explain the bluer bulges at lower redshifts. In support of the near-IR results and the monolithic view, other surveys find uniformly red E-S0 (Im *et al.* 2002) at the $z \sim 0.8$ epoch, with little evidence that any blue spheroid candidates are genuine progenitors of luminous spheroids today (Im *et al.* 2001).

As emphasized by Menanteau *et al.* (2001), the properties of field spheroids versus cluster galaxies provide powerful diagnostics of formation mechanisms. Using cluster E and E/S0 (not S0) as a benchmark for old stellar populations, they estimated "that at $z \sim 1$ about half the field spheroidals must be undergoing recent episodes of star formation." Moreover, as emphasized by the work of Benson *et al.* (2002), the resolved colors of spheroids are particularly effective probes of their formation history.

Here, we undertake a robust, head-to-head test of whether the resolved spheroid colors of galaxies from one cluster at redshift $z \sim 0.83$ differ from those of field spheroids at the same redshift. By decomposing galaxies into spheroid (bulge) and disk subcomponents, we avoid the confusion and uncertainties of prior surveys that included disk light in their estimates of spheroid colors. Our use of quantitative measurements of bulge to disk ratios also avoids relying on subjective visual morphological classifications to define the sample. Finally, the photometry for both samples uses nearly the same procedures and uses HST images of comparable quality. Our experiment thus reduces the need to correct for different and possibly unknown systematic and random errors.

We adopt a Hubble constant H_o = 70 km s^{-1}Mpc^{-1} and a flat cosmology with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. Our photometry is in the Vega system and throughout the paper, V will refer to V_{606} and I to I_{814} for the WFPC2 data from *HST*. Note that at redshift $z \sim 0.83$, $V-I$ is

* field refers to regions outside of rich galaxy clusters

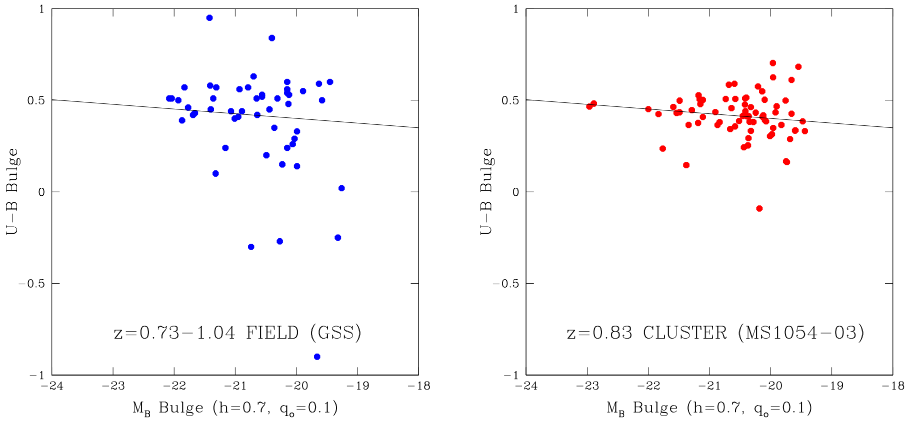

Fig. 1.1. $U-B$ vs M_B for bulges within galaxies in the rich redshift $z \sim 0.83$ cluster MS1054-03 and in the field at redshifts z from 0.73 to 1.04. Local Sbc galaxies have $U-B$ colors about 0; at our high redshift, this is roughly the division between red and blue stellar populations. The solid line is from a fit to color-magnitude relation of the galaxies in cluster MS1054-03 by van Dokkum *et al.* (2000). In contrast to our colors using GIM2D, the colors from van Dokkum are half-light colors of the galaxy, with no explicit separation of disks from bulges. Note that the field spheroids are on average clearly redder, i.e., above this line, while the cluster spheroids are roughly the same color or possibly a bit redder.

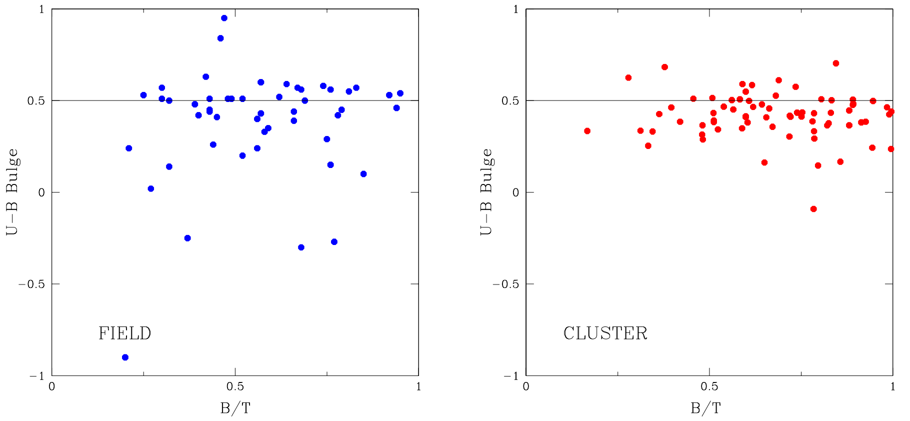

Fig. 1.2. $U-B$ of the bulges vs B/T for cluster and field galaxies from previous figure. Note that the very red colors are roughly independent of the B/T.

very close to restframe $U-B$ and I is close to restframe B, thus minimizing the uncertainties of K corrections.

1.2 Observations

Cluster MS1054-03 at redshift $z \sim 0.83$ was chosen for analysis since it is among the best observed distant clusters. The cluster has relatively deep (6600s in each of V and

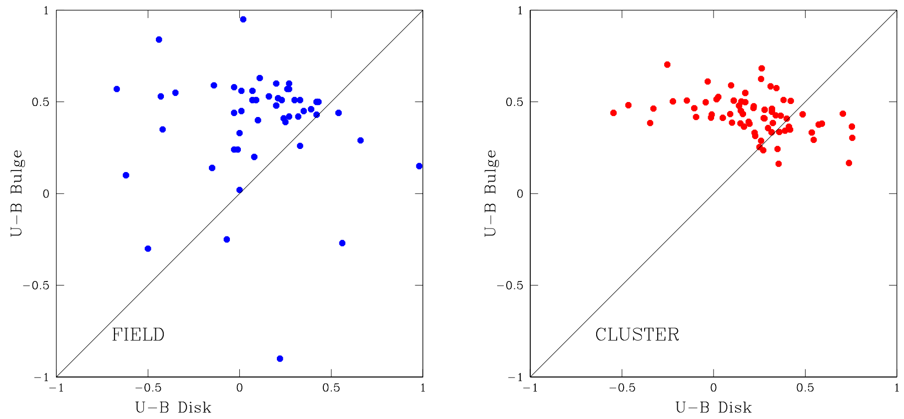

Fig. 1.3. $U-B$ bulges vs $U-B$ disks for cluster and field galaxies as in previous two figures. Note that any correlations of colors between bulges and disks are very weak for these luminous spheroids, so any secular processes (which predict high correlations) are likely to be minor factors.

I) and extensive (6 pointings of WFPC2 covering about 30 square arcmin of the region) *HST* imaging in V and I (van Dokkum *et al.* 2000). It also possesses over 100 redshifts from multiobject spectroscopy (Tran, private communication). Flat fielding and cosmic-ray removal of the *HST* images are described in detail by van Dokkum *et al.* (2000) who also measured colors and magnitudes via aperture photometry for the galaxies with spectroscopic redshifts.

Since our goal is to isolate the spheroid component, the reduced *HST* V and I images were reanalyzed with our own photometry package (GIM2D: see Simard *et al.* 2002 for details) to separate the luminosities and colors of the spheroids and disks. GIM2D fits each object in an image with a PSF-convolved 2D two-component model. One component that we dub as the spheroid or bulge is assumed to follow an $r^{1/4}$ profile that characterizes many luminous spheroids; the other we dub as disk is fit with an exponential profile. Based on our experience in working with GIM2D (Simard *et al.* 2002), reliable two-band colors for compact spheroids are derived by simultaneous fits of the profile parameters and the adoption of the simplifying assumption that color gradients for either of the subcomponents are small. One image in each filter is used in GIM2D. The spheroid and disk centers, sizes, orientation, and shapes are constrained to be the same, while the bulge-to-disk ratio and total luminosity are left to float. Due to the undersampling of the PSF by the relatively large pixels in WFPC2, GIM2D does not perform well with dithered and stacked images with subpixel shifts. GIM2D thus has the option to process a series of non-rotated images *in a single filter*, each with its own set of PSF's, but cannot yet undertake simultaneous fits with multiple images with differing filters. The cluster has 3 pairs of offset images in each of V and I. As a workaround to the limitations of GIM2D, we first fit each object with the 3 pairs of I images. The I was chosen since the bulges were generally very red and thus had higher S/N in I than V. Except for the luminosity and bulge-to-disk ratio, all the other measured parameters from I were locked when the V images were fit. The conversion of the measured

I and $V-I$ to restframe M_B and $U-B$ were made using the method described by Willmer *et al.* (2003), but yield nearly identical results to those of van Dokkum *et al.* (2000).

The field spheroids were chosen from a sample of galaxies within the V and I *HST* images of the "Groth Strip Survey" (GSS), a "chevron strip" of 28 WFPC2 pointings oriented NE to SW at roughly 14:17+52 at Galactic latitude $b \sim 60$ deg. The galaxies were constrained to have about the same redshifts as MS1054-03, namely z between 0.73 and 1.04, where the spectroscopic redshifts were measured by *DEEP**. From a total sample of over 600 redshifts (Weiner *et al.* 2003), about 200 fell within our redshift range. Except for one ultra-deep pointing with 24,400s in V and 25,200s in I, the other HST images in GSS were comprised of a combined image in I of 4400s and in V of 2800s. As detailed by Simard *et al.* (2002), GIM2D processing of the 2800s V and 4400s I were made in each separately and simultaneously. To check that the locking procedure for the cluster photometry using GIM2D yielded essentially the same results as the simultaneous mode for the field, we adopted and locked the parameters from the 4400s I (except for luminosity and B/D ratio) for 20 field galaxies in GSS and used these to process the multiple images in V. The conversion of the input I and resultant $V-I$ to restframe M_B and $U-B$ were as mentioned above. No significant differences beyond random noise were found in the results between the two methods.

Relying on our prior experience in working with GIM2D, the final spheroid samples for both cluster and field were furthered constrained to meet three additional criteria:

1) the spheroid component had to be brighter than $I = 23.006$ so as to yield reliable photometry;

2) the spheroid half-light sizes were larger than one third of a pixel,i.e. 0.03 arcsec, again to assure reliable photometry of a probable spheroid; and

3) the spheroids had to have half-light sizes smaller than the half-light sizes of the disk subcomponent *or* the spheroids were dominant with more than 2/3 of the total luminosity, i.e., B/T > 0.67.

The last criterion was needed to reject cases where GIM2D fits a central probable spheroid with a small exponential component and the outer probable disk with an $r^{1/4}$ component. Such structures appear to exist in nature but we chose to reject such anomalous spheroids from this survey. These restrictions resulted in reducing the full sample of 110 MS1054 cluster members processed with GIM2D to 71 and the GSS field sample to 52.

1.3 Results

The color magnitudes (CM) of the spheroids are displayed in Fig. 1.1. The main result is clear: the slope, color, and dispersion of the CM are very similar between cluster and field galaxies, except for slightly more blue excursions in the field sample. Relative to the solid line showing the half-light aperture colors of the cluster early-type galaxies as measured by van Dokkum *et al.* (2000), we find the spheroid colors to be on average the same or slightly redder, especially for the field spheroids. We find these CM results to be independent of the bulge to total (B/T) ratio (see Fig. 1.2). With additional tests and GIM2D measurements to be presented elsewhere (Datta *et al.* 2004, in preparation), these findings also appear to be independent of the distance from the cluster center (i.e., average density), the color of the disk, and the inclination of the disk. Assuming the shallowness

* Deep Extragalactic Evolutionary Probe: see URL http://deep.ucolick.org/

of the CM slope (-0.03 in $U-B$ per B mag in luminosity), the independence also applies for the luminosity of the spheroid or the luminosity of the total galaxy. We also find that the spheroid colors are almost always the same or redder than the disk for both cluster and field galaxies (see Fig. 1.3). This result has already been found elsewhere but only for field galaxies (Abraham *et al.* 1999a; Ellis *et al.* 2001). This finding is expected in either the monolithic or merger models. Our uniformly red colors for the spheroids *disagree* with claims of 30% to 50% fractions of spheroids or spheroidals being blue in the field at this redshift.

Blue spheroids that were found in the field (see Fig. 1.1) are a small fraction ($< 15\%$) of the total sample and have properties that do not match well to those expected for a young, massive spheroid in formation. Any strong starburst counterparts to luminous bulges or E-S0's ($M_B < -20$) would be expected to be even brighter by perhaps several magnitudes, and with very blue colors. The ones in our sample generally have lower luminosities (see Fig. 1.1.), about half have low B/T (see Fig. 1.2), about half have disks that are redder, some show low values of internal kinematics indicating very low masses (Im *et al.* 2001, Koo *et al.* 2004), and on average have lower half-light surface brightnesses than even local spheroids of the same luminosity so that after fading they would not match the surface brightness of spheroids today (see Koo *et al.* 2004). Thus we find no good evidence for a signficant population of *genuine* blue spheroids at redshifts $z < 1$.

Using the same half-light surface brightness measurements as a gauge of the luminosity evolution of spheroids, assuming sizes and light profiles have been stable, we find about 1 magnitude of evolution by redshift $z \sim 1$ in the field. What is puzzling is that the spheroid colors are so very red while the luminosity is changing so significantly. This cannot be easily explained with star formation histories involving only passive evolution fo the stars after an earlier, initial, short burst of spheroid formation. Most stellar population models (e.g., recent Bruzual and Charlot 2003) predict a reddening by about 0.2 in $U-B$ between redshifts $z \sim 1$ and today for plausible formation epochs using standard Salpeter IMF and solar metallicities. Depending on whether local spheroids have $U-B$ colors closer to 0.5 or 0.6, we find none to at most a 0.1 change in color. One plausible scenario to explain our observations is to propose that the initial burst involved the formation of stars of super-solar metallicity followed by a "drizzling" of star formation to keep the colors close to $U-B = 0.5$ from redshifts $z \sim 1$ to today (see Gebhardt *et al.* 2003 and Koo *et al.* 2004 for more details). This proposed additional, but mild amount of later star formation is supported from numerous other observations that show emission lines among distant E-S0 galaxies (e.g., Schade *et al.* 1999, Willis *et al.* 2002, van Dokkum & Ellis 2003). We confirm these findings with an even more restrictive subsample of galaxies whose GIM2D photometry show that both the disk and bulge are very red ($U-B > 0.25$). This restriction avoids the possibility that a very blue, but minor disk component is contributing to the emission lines seen in the spectra, rather than the bulge itself. More specifically, among the 10 most luminous such galaxies in the field, 8 show [OII] emission lines, indicating star formation rates of roughly one solar mass per year.

Before concluding, a few caveats and possible weaknesses of the survey should be explicitly stated. The results apply only: 1) to spheroids that are luminous ($M_B \lesssim -19.5$) (this opens the possibility that lower luminosity spheroids may have experienced a different formation history, such as with secular evolutionary processes); 2) to galaxies that possess only two subcomponents, with the spheroid being well represented by an $r^{1/4}$ profile while the disk has an exponential; and 3) to galaxies that do not have large enough color gradients in either of the subcomponents to change the results. Our field sample with only 52 galaxies is small, so that different properties might apply to 10% to 20% minorities. The field sample is also biased to galaxies with easy redshifts, and thus perhaps stronger emission lines.

1.4 Conclusions

Our color-magnitude results challenge hierarchical models of galaxy formation that predict colors of distant ($z \sim 1$) field spheroids would differ from that of cluster spheroids. Our measurements also disagree with claims by other surveys that significant (30% to 50%) populations of very blue field spheroids exist at early epochs near $z \sim 0.8$. Our findings are instead best explained by luminous field spheroids being predominantly an uniformly old (formation epoch at redshifts $z > 1.3$, metal-rich stellar population, like their cluster counterparts. But to explain nearly constant red colors since redshifts $z \sim 1$, the field spheroids are proposed to harbor small residual star formation.

1.5 Acknowledgments

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