Formation and Evolution of Galaxy Bulges
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Properties of luminous spheroids at redshifts $z \sim 1$ from Keck and HST

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Abstract. Three new and still on-going surveys that combine the power of spectroscopy or adaptive optics from the Keck Telescopes with HST images are DEEP, AEGIS, and CATS. The advantages of each for the study of distant bulges are accompanied by a few highlights. We find that the vast fraction of luminous distant bulges appear very red, independent of the bulge luminosity, bulge fraction, disk color, and environment. Yet early-type galaxies appear to be relatively young at redshifts $z \sim 1$, are less numerous then, host many X-ray AGN's with some that are highly obscured, and have low but increasing dry-dry and dry-wet merger rates over time.

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1. DEEP and AEGIS

DEEP (Deep Extragalactic Evolutionary Probe) was initiated 16 years ago to use the Keck 10 m Telescopes for a major spectral survey of faint field galaxies. The use of DEIMOS (DEep Imaging Multi-Object Spectrograph), commissioned in 2002 (Faber *et al.* 2003), divides DEEP into two phases. The first (DEEP1) used pre-DEIMOS spectrographs on Keck as well as images from the Hubble Space Telescope (*HST*) to undertake several pilot programs that were designed to establish the technical feasibility and scientific scope of the main survey (DEEP2) in the second phase (Davis *et al.* 2003). DEEP1 (see Vogt *et al.* 2005 for overview) included redshift surveys up to $z \sim 3$, study of disks and bulges as well as compact galaxies and AGNs, luminosity functions, chemical abundances, and kinematics.

DEEP2 is distinguished from previous distant field galaxy redshift surveys by its large sample size of about 35,000 galaxies that reach faint enough ($R_{AB} \sim 24$ mag) to access typical galaxies at redshifts $z \sim 1$ and by its high spectral resolution. The survey uses BRI two-color diagrams to preselect galaxies at redshifts $z > 0.7$ for three of its four fields. Each of these three cover about one square degree. The 4th field is the Extended Groth Strip (EGS) covering half the area (0.5 square degrees) for which no redshift preselection is made. This was done to better support a suite of high quality and deep multiwavelength surveys ranging from Chandra X-ray surveys, V and I imaging with HST ACS, IRAC and MIPS Spitzer imaging, to VLA radio maps, all under the aegis of the All-wavelength Extended Groth International Survey (AEGIS: Davis *et al.* 2007). An upper limit of $z \sim 1.45$ for all fields is set by the accessibility of [OII] 3727Å up to the red limit of our spectral range (∼9100Å).

DEEP2 is particularly valuable for the study of bulges and spheroids. Its depth reaches redshifts $z \sim 1$ or 7 Gyr, far enough back in time when spheroids and bulges in secular evolution scenarios or in CDM models are expected to be young or actually forming.

DEEP2 uses tilted slits and a spectral resolution high enough ($R \sim 5000$) to measure internal galaxy kinematics (rotation curves and linewidths), that provide a powerful new dimension related to the dynamical masses of galaxies. These dynamical masses are intimately tied to dark matter halo masses, which in turn are the fundamental components of galaxies best understood from theoretical simulations. Such precision velocities also allow reliable detection of galaxy groups, measure environments on Mpc scales, and decontaminate close pairs kinematically. The large sample sizes (few 10,000's) and high surface density (~7 per sqarcmin) are great enough to yield good measures of the luminosity function of subclasses of galaxies such as red galaxies and of the environment, detect rare sources such as massive spheroids, and enable spectral stacking of spheroids of different luminosities, colors, and environments to study their ages, metallicities, and emission line properties. Our survey is, however, not large enough to contain one or more rich clusters of galaxies, i.e., very high density environments. Having four fields mitigates against cosmic variance, especially of strongly clustered objects such as massive spheroids. Most important of all, DEEP1 and DEEP2 are both done and available to the public.

In the case of AEGIS, its advantages for the study of bulges and spheroids includes all those already ascribed to DEEP2 except for the mitigation of cosmic variance by using four fields. An additional strength includes having HST images in two filters (versus one in COSMOS) that enables *critical* corrections to restframe colors and luminosities from subcomponent photometry. Relevant questions to be tackled include: are distant bulges predominantly red? Do distant spheroids show color gradients? Do distant bulges and disks have colors that support secular evolution? The survey depths at other wavelengths in AEGIS are among the deepest outside of the GOODS fields and covers significantly more area. Though rare and likely related to bulge formation and mergers, AGNs and dusty, strong starbursts are well sampled with AEGIS. And like DEEP, most of the AEGIS surveys are now complete. For more information about the DEEP, DEEP1, DEEP2, and AEGIS projects and access to publicly available data, the reader is referred to the following URL's: http://deep.ucolick.org/, http://deep.berkeley.edu, and http://aegis.ucolick.org.

2. Highlights Related to Bulge and Spheroid Science from DEEP and AEGIS

DEEP (Willmer *et al.* 2006, Weiner *et al.* 2005) has confirmed the Bell *et al.* (2004) finding that distant field galaxies exhibit a clear color bimodality similar to that seen in local SDSS galaxies (Strateva *et al.* 2001). While the distant red galaxies continue to be dominated by early-type galaxies with luminous spheroids, an increasing fraction of the red galaxies appears diffuse and/or have later Hubble type (Weiner *et al.* 2005). Several different studies all support an overall increase in the luminosities of red galaxies back in time, including the study of the fundamental plane (Gebhardt *et al.* 2003) or of the luminosity function (Faber *et al.* 2007, Im *et al.* 2002). Bulges also appear to have been brighter in the past as expected from simple passively evolving stellar populations (Koo *et al.* 2005a). Finding that the luminosity density of just the red galaxies have been nearly constant over time and with the evidence for luminosity evolution, Faber *et al.* (2007) conclude that stellar masses of the red galaxies near L^* have at least doubled since a redshift $z \sim 1$. Based on a much larger sample, the DEEP2 finding thus supersedes our earlier claim for little evolution (Im *et al.* 2002). Whether the most luminous red galaxies (>3 L^*) have experienced a similar increase remains unclear.

Our main result (Koo *et al.* 2005a) for bulges is based on a study of their luminosities and colors, after they had been separated from any overlapping disks. The separation is

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achieved by using the GIM2D galaxy structure decomposition program (Simard *et al.* 2002). The distant bulges were chosen to be bright enough for good S/N of the derived parameters; no morphological cut was applied. Our approach reduces or avoids any progenitor bias (van Dokkum *et al.* 2001). Our bulge photometry does not suffer the level of contamination by disks when adopting methods that mix S0's and ellipticals or use integrated or aperture colors. A valid concern is that many galaxies are poorly characterized by only a small set of parameters.

Assuming that redder colors among bulges are mainly due to older ages rather than dustier or more metal-rich systems, we can test simplified expectations from proposed scenarios for the formation of bulges. Monolithic collapse models would, e.g., predict that bulges/spheroids are uniformly very old and thus red at redshifts $z \sim 1$. Secular evolution models would instead predict that the colors of the bulges would be similar to the disks from which they were formed or perhaps even bluer since the bulges may be formed more recently than the disk. ΛCDM models, in contrast, propose that bulges are formed from major mergers over an extended period of time, with any disks forming later. This would predict that bulges have a range of colors but are redder than disks. Moreover, due to the earlier times of formation of rich clusters, bulges in the field should be bluer than those in rich clusters.

The key result is simple (Koo *et al.* 2005a): bulges more luminous than $M_B \sim -19$ are predominantly red, regardless of the color of the disk, bulge to disk ratio, or bulge luminosity. The red colors are also found to be independent of environment as measured by their distance from the center of a rich cluster of galaxies at redshift $z \sim 0.8$. Fig. 1 (Koo *et al.* 2005b) shows these results. Moreover, these studies show that luminous bulges are almost always redder than their disk hosts, when present, and that the color-magnitude slope is shallow and the color scatter is small. The simple interpretation is that luminous bulges are predominantly old, with metallicity rather than age being the source for the color-magnitude slope. One puzzle is that the colors appear to be too red to be consistent with simple passive evolution from an early burst. By finding only weak dependence of the colors on the inclination of the disk, dust extinction is excluded as the primary cause. Whether 'drizzling' of gas and continued, but minor, star formation; some change in the stellar population models; or some, as yet unidentified, cause is the explanation remains unclear.

Instead of relying only on colors, more detailed information from stellar absorption lines should improve the constraints on both metallicity and age. Single spectra based on one hour exposures on even a 10-m telescope tend, however, to have insufficient S/N for our distant galaxies. Taking advantage of the full DEEP2 sample of over 30,000 spectra, Schiavon *et al.* (2006) show that stacking a small subset of 100's of spectra of distant red galaxies is able to yield information from weak absorption lines. Using this approach, they find that the derived ages and metallicities from the spectra and colors from photometry from combined SDSS and DEEP2 data are inconsistent with predictions from simple, passively evolving, single-burst models. Some amount of slight, but continuing, star formation (Gebhardt *et al.* 2003) or rapid quenching of continuous star formation (Harker *et al.* 2006) appears to be needed.

Our final DEEP2 highlight is the result of Lin *et al.* (2007), that, while the overall evolution of the merger rate appears to be low (Lin *et al.* 2004), the fraction of dry-dry or dry-wet mergers appear to be increasing with time since redshifts $z \sim 1$, while wet-wet mergers appear to decline. The dry-dry mergers are especially interesting as they have been proposed as the dominant mechanism to build up the most massive spheroids. The simplifying assumption for this work is that dry systems with little

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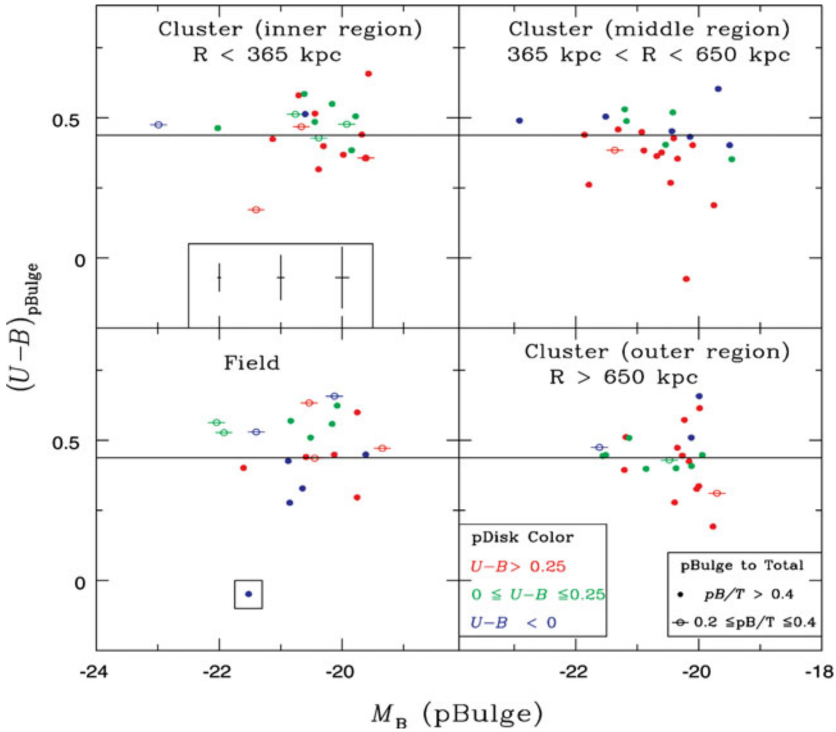

Figure 1. $U-B$ vs M_B for bulges within galaxies in the rich redshift $z \sim 0.83$ cluster MS1054-03 and in the field at redshifts z from 0.73 to 1.04. Local Sbc galaxies have $U-B$ colors about 0; at our high redshift, this is roughly the division between red and blue stellar populations. The solid horizontal 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 derived 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.

gas are galaxies that are red while those with significant amounts of gas (wet) are blue.

AEGIS also provides useful constraints on the evolution of bulges. For example, Nandra *et al.* (2007) find that the Chandra X-ray sources in our field lie predominantly among the luminous and redder galaxies, with tantalizing evidence for those with hard X-ray spectra, i.e., highly obscured AGN's, to reside even among normally non-dusty, early-type, red galaxies. Another result from Le Floch *et al.* (2007) show from a broad suite of multi-wavelength observations that a hyper-luminous infrared galaxy has its energy produced equally between star formation and AGN. This result suggests that some very active systems are simultaneously building up their supermassive black hole and its associated host spheroid.

3. CATS

CATS is an adaptive optics (AO) survey aimed as a near-IR study of the structural, chemical, star formation, and kinematic evolution of distant field galaxy subcomponents on sub-kpc scales (Larkin *et al.*, in preparation). Using AO on an 8–10 m telescope yields near-IR diffraction-limits of 0.05 arcsec, which is a very close match to HST's optical resolution and corresponds to the sizes of bulges/spheroids, disks, bars, spiral arms,

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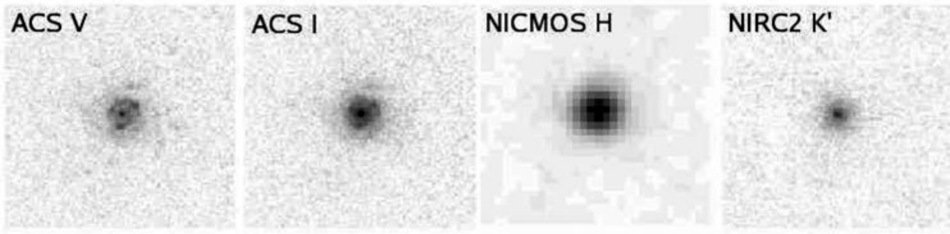

Figure 2. These $6'' \times 6''$ images of GSS 044_6719 with north up and east to the left show the superb resolution achieved in the K' band ($0.16''$ FWHM) with the Keck II laser guide star adaptive optics system and the NIRC2 camera in wide field mode ($0.04''$ pixels). This galaxy has a redshift z = 0.67 and clearly shows a very compact, red, bulge-like core and a bluer, outer disk. For comparison, note the HST NICMOS3 H band image which has pixels of $0.20''$ and thus under-samples the PSF of $0.35''$ in H. The HST ACS images have FWHM about $0.10''$. See Steinbring *et al.* (2007) for details.

and merger/interaction or lensing signatures at redshifts $z > 0.5$. This match between HST and Keck drove the CATS strategy to observe the well-studied HST survey fields: GOODS, COSMOS, GEMS, & EGS. These regions are also highly leveraged by deep Chandra, XMM-Newton, GALEX, and Spitzer data from space and optical, near-IR, submm, and radio data from the ground.

Compared to the optical, the near-IR is well suited for the study of bulges by providing superior penetration through dust and having higher sensitivity to old red stars. For high redshift bulges, the near-IR measures the restframe optical and includes the important $H\alpha$ and [NII] lines for spectroscopy. Keck II now routinely provides laser guide star (LGS) AO (Wizinowich *et al.* 2006), which has opened new doors for the study of bulges as well as many other areas of astronomy (see Liu 2006 for an overview of the pros and cons and promise of AO). With LGS AO needing tip-tilt stars brighter than only 18th mag within ~ 60 arcsec (van Dam *et al.* 2006) and having good characterization of the off-axis point spread function (Steinbring *et al.* 2005), CATS now has access to 20% or more of the special HST galaxy survey fields. This coverage enables over 1500 galaxies to be accessible to AO. Prior to LGS, only about 1% was reachable on Keck since much brighter natural guide stars of 12th mag were needed (Wizinowich *et al.* 2000).

4. Highlights for Bulge and Spheroid Studies

To date, CATS has obtained AO data with Keck II for about 10 pointings or 5 square arcmin with the NIRC2 camera in the deep HST survey fields. One Chandra X-ray galaxy in GOODS-S was found to have two red nuclei for which the 4 filter HST ACS photometry in the optical indicated either old stars or dusty, younger stars. The AO K-band photometry provided the critical discrimination and suggested that both were old. Thus we are witnessing a "dry merger" (Melbourne *et al.* 2005). In another study, M. Barczys (PhD 2006) exploited the higher sensitivity to stellar mass of near-IR photometry to discover that many of the apparent major mergers that are expected to form ellipticals with roughly equal luminosities seen in the HST optical images are in fact minor mergers with unequal stellar masses. Finally, in another pilot study within CATS (Steinbring *et al.* 2007; see Fig. 2), we decomposed a galaxy into bulge and disk components from HST optical and Keck AO near-IR images to study the colors of their stellar populations; the bulge was of relatively low-mass and had colors most consistent with being of intermediate age and dusty. Being of low luminosity and residing in a late-type spiral, it is thus more likely to be a pseudobulge (Kormendy and Kennicutt 2004).

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CATS plans to acquire more LGS AO images, mainly to study the host galaxies of AGNs and the colors of bulges and disks. With the advent of OSIRIS (Larkin *et al.* 2006), an AO-compatible, near-IR spectrograph with an integral field unit, CATS is poised to gather high spatial resolution 2-D spectroscopic data of bulges and spheroids. A major goal of CATS is to provide the community with good quality AO data with which to explore their scientific potential. To this end, CATS will be releasing some of the Keck AO data in 2007 (http://www.ucolick.org/~jmel/cats_database/).

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