Evolution and Environment of $0.2 < z < 1.1$ Galaxies in the COSMOS/Subaru Survey

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3 May 2004

Abstract

Recent galaxy evolution studies using data from the SDSS, GOODS, and GEMS surveys have presented surprising results on the evolution of morphological parameters with redshift. However, both GOODS and GEMS (studying high-redshift samples) cover relatively small sky areas, and the results derived from them may be influenced by field-to-field variance in large-scale structure, since galaxy properties can be different in different density environments. The COSMOS survey, with its continuous 2 square degree sky coverage and multi-wavelength observations, provides an opportunity to compare galaxy properties at different redshifts over a variety of galaxy environments (cluster, group, or field). I propose to measure the half-light radii, Petrosian radii, concentration and asymmetry parameters, and bulge-to-disk ratios in the rest-frame B band, for $0.25 < z < 1.1$ galaxies in the COSMOS field, plus the rest-frame $U - B$ colors. Then, I will investigate how these properties change as a function of redshift and environment. I propose to carry out this analysis using the $BVr'i'z'$ Subaru images of the COSMOS field and the photometric redshifts that will be derived from the survey's collection of broadband photometry. I will measure the galaxies at whose redshifts the central wavelength of one of the Subaru bands corresponds to the rest-frame B band, and construct parameter distributions for each redshift bin. Magnitude, surface brightness, and/or size limits may be used to restrict the data sample, or corrections will be applied, to reduce the effects of systematic biases.

1 MOTIVATION

Galaxy evolution is a subject crucial to cosmological studies in astronomy (e.g. tests of the Universal geometry and expansion), and while we have a general knowledge of what processes cause galaxies to change over time, we do not yet know how these processes affect the global population of galaxies. Our intrinsic inability to watch individual galaxies evolve over time is a large factor in this problem. We can only identify how galaxies evolve by examining changes in statistical distributions of their properties over the look-back time of the Universe. Another factor contributing toward our continuing ignorance is that galaxy surveys and samples, from which we must construct statistical distributions, are plagued by systematic effects. Some effects are well understood and we may quantify them and correct for them (e.g. bandpass shifting), some we know exist but cannot correct for (e.g. cosmic variance), and some systematic effects may exist which have not even been identified. A further complication is the difficulty in quantifying galaxy evolution, as it is difficult to quantify galaxy morphology itself in a physically meaningful way. The creation of the Hubble sequence (Hubble 1926, 1936) began studies of galaxy morphology, but it is limited due to its subjective and qualitative nature. New ways of breaking down the observed properties of galaxies in an automatic and objective manner have been introduced (e.g. the CAS parameters; Abraham et al. 1994, 1996; Schade et al. 1995; Conselice 2003), but it is unclear which system of parameters yields the best description of a galaxy.

So far, there is no easy way to combat all of these effects in a single study without a significant investment of observing, computing, and human resources, as Lilly et al. (1995b) suggest that evolutionary trends determined internally from self-consistent data sets be regarded as more reliable. Several large galaxy surveys have nevertheless been recently undertaken, hoping to combat the systematic effects of previous galaxy evolution studies with self-consistent data and new technology (e.g. SDSS at low redshift, York et al. 2000; at high redshift CFRS, Lilly et al. 1995a; GOODS, Giavalisco et al. 2004; GEMS/COMBO-17, Rix et al. 2004; and DEEP2, Davis et al. 2002). However, few of these new surveys examine how the density of galaxy environments affects the statistical distributions they derive of galaxy structural properties, especially at high redshift. It is well known, through the existence of the morphology–density relation and the Butcher-Oemler effect at both low and high redshift (Dressler 1980; Smith et al. 2004; Butcher & Oemler 1984), that local density plays some part in determining the morphology and structure of a galaxy. Indeed, Kauffmann et al. (2004) find in their study of 120,000 $0.03 < z < 0.1$ galaxies from the SDSS that the stellar mass distribution, the specific star formation rate (SFR/$M_\star$), and nuclear activity are strongly dependent on local density, while size and concentration appear to be independent of density. We can try to resolve the question of whether galaxy morphology is primarily caused by nature (galaxy properties were imposed early on during formation, so they are intrinsic), or nurture (a product of processes that occur over a Hubble time and can vary with location in the Universe) by examining the relation between local density and structure for high-redshift galaxies, at least up to the point where our system of galaxy classification holds, ($z \sim 1$, Abraham 1999).

Previous deep surveys of high-redshift galaxies have not covered sufficient contiguous areas of the sky to be able to adequately sample the range of galactic environments. Also, these studies have not covered areas sufficient to rule out cosmic variance as a significant factor in their results, and have suffered from small sample sizes. Thus, studies of galaxy structure as a function of environment have been difficult with existing data. However, a new deep survey, COSMOS, has begun, led by Nick Scoville, which plans to cover 2 continuous square degrees at wavelengths ranging from the X-ray to the radio regime, with the specific goal of probing large-scale structures and matter density in the universe. The COSMOS survey thus presents an unprecedented opportunity to study the structural properties of high-redshift galaxies as functions of both redshift and environment in a larger, more statistically significant sample, of which I would like to take advantage.

Goal of Thesis: My goal is to evaluate trends in galaxy color and structure with redshift, by measuring fundamental parameters of galaxies in the COSMOS field. I will then see how these trends vary with galaxy environment. I intend to do this while minimizing as much as possible biases caused by selection effects, surface brightness dimming, and bandpass shifting.

To carry out such a study, I will minimally require deep, high-quality imaging, in several filters for rest-frame comparisons, and redshifts of the galaxies in the imaged field. This data, and more, will be provided by members of the COSMOS survey team over the course of the next several years.

2 THE COSMOS SURVEY: A FOUNTAIN OF DATA

The COSMOS survey is a deep, multi-wavelength, wide-field survey designed to probe the formation and evolution of structure in the Universe, over the size range of galactic to the largest known size structures ($\sim 10^{14}\,M_\odot$). The survey is an international collaboration, led by Nick Scoville. At its heart of is I-band (F814W) HST-ACS imaging of a 2 square degree, equatorial field, which is a HST Treasury Project for HST Cycle 12-13. With 581 pointings over the field and an integration time of 1 HST orbit per pointing, the survey expects to detect over 10^6 objects with $I < 27$ mag (10σ, AB system).

To supplement the HST data, additional deep optical-band data is being obtained with ground-based telescopes. Imaging of the full 2 square degree field with Suprime-Cam on the Subaru telescope (PI: Y. Taniguchi) in the $BVr'i'z'$ filters has been obtained (to depths of 25-27 AB mag), as well as u^*, i, and K-band data from CFHT (PIs: O. LeFèvre & D. Sanders) to depths 26.9, 24.9, and 23 mag, respectively, and K_s data to $K_S \sim 21$ from the 4-m telescopes at Kitt Peak and CTIO (PI: B. Mobasher). Much of this imaging data will be used to measure photometric redshifts of all objects in the field to $I \sim 25.5$, with the Bayesian method (Benítez 2000) employed in Mobasher et al. (2004). Low-resolution ($R \sim 300$) spectra of $\sim 50,000$ objects in the survey field with $I < 23$ will be obtained with the VIMOS multi-object spectrograph on the VLT (PI: J.–P. Kneib).

Multi-wavelength imaging of the COSMOS field includes: XMM-EPIC imaging in the 0.5–2 keV and 2–10 keV bands (PI: G. Hasinger), GALEX imaging (PI: D. Schiminovich) in the FUV and NUV bands (FUV to 26 mag, NUV to 25.8), CSO-BOLOCAM imaging of the central square degree at 1.1 mm (PI: A. Blain), and HST-NICMOS parallel fields (PI: D. Calzetti) in H-band. Proposals have been submitted to obtain more wavelength coverage of the COSMOS field, including a *Chandra* proposal (PI: M. Elvis), a *Spitzer* proposal (PI: D.

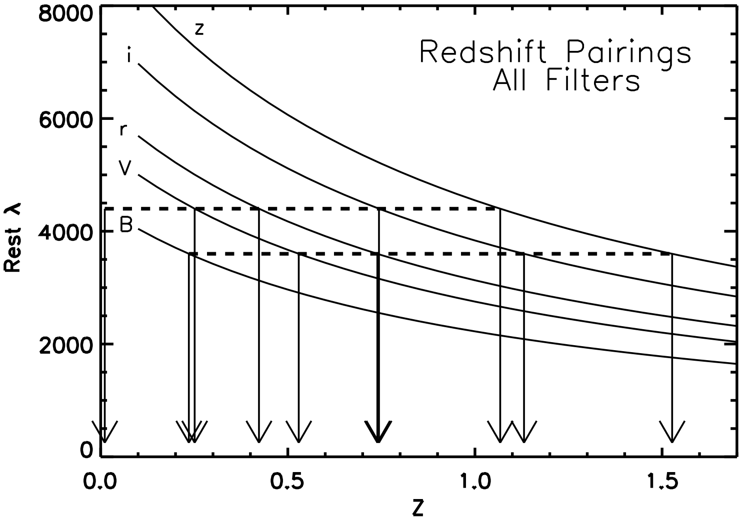

Figure 1: Rest wavelengths to which Subaru filters are shifted with changing redshift. The horizontal lines indicate rest-frame filters, and the arrows pointing down from them indicate the redshift at which a particular Subaru band matches that particular rest-frame wavelength.

Sanders) to image the field with IRAC (near-IR) and MIPS (mid-IR), and a VLA proposal to image the full field at 20 cm (PI: E. Schinnerer).

Out of this enormous wealth of COSMOS data, I plan to primarily use the Subaru Suprime-Cam imaging to carry out my study. As shown in Figure 1 below, the $BVr'i'z'$ imaging will allow me to measure galaxy properties in the rest-frame B-band for galaxies in redshift bins centered on $z \sim 0.25$, $z \sim 0.42$, $z \sim 0.74$, and $z \sim 1.07$.

The Suprime-Cam instrument at Subaru is a wide field $(34' \times 27')$ imager mounted at the prime focus of the 8.2-m telescope. It consists of 10 2048×4096-pixel high-QE CCDs aligned in 2 rows of 5 chips with $16''$ gaps between them. Each 15-μm pixel corresponds to $0.2''$. Though the instrument is not part of an adaptive optics system and therefore has resolution limited by the Earth's atmosphere, it consistently delivers superior image quality, with a point-spread-function (PSF) that varies smoothly across the field of view. The Suprime-Cam data was collected in two separate observing runs in 2004 January and February. Table 1 lists the properties of the resulting dataset. The magnitude limits should allow us to observe a $\sim L^\star$ galaxy at redshift $z = 1.1$. The data are made available to the COSMOS team, by our collaborators in Japan, in a fully reduced form, ready for analysis.

I plan to use the photometric redshifts computed from the broadband optical imaging to sort the objects by redshift to determine my sample. This is necessary as the spectroscopic redshifts for the full field will not be available for at least another year. The photometric redshifts are expected to be accurate to $\sigma(\Delta z/(1 + z_{spec})) \leq 0.11$, based on the use of the same technique on GOODS data (Mobasher et al. 2004).

Filter	Eff. λ (Å)	Obs. Date	Eff. Exp. Time	Limit (3σ, AB)	Seeing ($''$)
B	4448	2004 Jan	70.3m	27.3	0.5-0.8
V	5505	2004 Feb	42.3m	26.9	0.5-0.8
r'	6261	2004 Jan	36.0m	26.9	0.5-0.8
i'	7672	2004 Jan/Feb	40.3m	26.6	0.4-0.6
z'	9097	2004 Jan	63.5m	25.6	0.5-1.0

Table 1: Characteristics of COSMOS Subaru imaging data.

3 GALAXY PARAMETERS OF INTEREST

With the ground-based data from the COSMOS survey, the most practical, physically meaningful parameters with which to characterize the structure of both early and late-type galaxies in the $0.2 < z < 1.1$ sample are listed below.

Galaxy Luminosity & Surface Brightness Galaxy luminosity is an indicator of the total stellar mass contained within a galaxy, and is known to depend on environment. The surface brightness profile of a galaxy indicates generally how both gaseous and stellar mass are distributed over the physical size of the galaxy, and may depend on environment. By measuring M_B and μ_B for COSMOS galaxies in different environments in my selected redshift bins, I hope to shed light on the distribution of mass in the Universe and how galaxy mass is assembled into larger structures.

Integrated Galaxy Color Measuring the integrated color of a galaxy indicates general characteristics of its resident stellar population, since stellar color is strongly dependent on mass, age, and metallicity. Galaxy color can be an indicator of the galaxy's global star formation rate, and is known, from the Morphology-Density relation (Dressler 1980) and the Butcher-Oemler effect (Butcher & Oemler 1984) for galaxy clusters, to depend strongly on redshift and environment. By measuring the rest-frame $U - B$ colors in the COSMOS sample, I intend to examine global stellar population changes over time in different galaxy environments. Specifically, I am interested in looking for the appearance of the Butcher-Oemler effect in the field as redshift increases. In addition, the evolution of the color-magnitude relation for elliptical galaxies can be explored.

Galaxy Size Measurements of the distribution of sizes of both early and late-type galaxies help constrain models of the formation and evolution of galaxies in the Universe. For example, the distribution of galactic disk sizes and its evolution with redshift help confirm or discredit hierarchical models of galaxy formation through its relation to a galaxy's angular momentum and help constrain models of the evolution of the galaxy luminosity function. Evolution in the size distribution of elliptical galaxies provides evidence of mergers of galaxies and also supports hierarchical models of galaxy formation. I will measure the sizes of both early and late-type galaxies in my redshift bins, to see if possibly, at higher redshift, galaxy size was correlated with environment. I will measure the Petrosian radius, r_p, as the size indicator for this study, using the

SDSS prescription (Stoughton et al. 2002), since the Petrosian radius is a metric radius and is an intrinsic property of the galaxy intensity profile. For comparison, I will also measure the half-light radii, r_h.

Galaxy Concentration & Asymmetry The concentration (C) and asymmetry (A) indices were introduced by Abraham et al. (1994, 1996) and Schade et al. (1995), respectively, to quantitatively distinguish between early, late, and irregular-type galaxies. The C index measures the ratio of light within an elliptical inner aperture to the light in an outer aperture, and is correlated with bulge-to-disk ratio. The A index is a measure of the rotational symmetry of a galaxy's light. I plan to use these parameters primarily to separate early-type galaxies from late-type galaxies, and identify possible irregular galaxies in the different density environments, but evolution in the distributions of these indices can also be explored, as in Kauffmann et al. (2004). I plan to use the definitions of C and A put forth by Bershady et al. (2000).

Bulge-to-Disk Ratio The bulge-to-disk ratio (B/D) for late-type galaxies generally indicates the prominence of the bulge in bulge+disk systems, and thus helps separate early-type spiral galaxies from late-type spiral galaxies along the Hubble sequence (Graham 2001). Measuring the change in B/D with redshift and environment may indicate the contribution of minor galaxy mergers to the structure of galaxies in different types of density fields.

I will measure these properties with combinations of publicly-available codes and my own routines and examine their distributions over different redshifts. Experimentation will be necessary to find the best way to measure each parameter, and I intend to devote a significant block of time during the next year to developing methods to analyze the data.

The determination of galaxy environment in the sample is also an essential component of this proposed study. I have not yet decided on a method of defining galaxy environment, and plan on working with my adviser and several other members of the COSMOS team who are carrying out galaxy environment surveys with the survey data. Eventually, I would like to define galaxy densities over volumes characteristic of dark matter halos, and use the results of X-ray images and dark matter/shear maps of the COSMOS field in concert to help define the location and size of mass overdensities. I could define local density based simply on number counts of galaxies within a metric aperture, but it seems a waste to not make use of the fantastic multi-wavelength, observational and theoretical, resources of the COSMOS survey.

4 POTENTIAL SOURCES OF BIAS

All studies of galaxy evolution in a magnitude-limited survey will suffer from bias and selection effects. The effects most likely to bias the results of my proposed study are the following:

Surface Brightness Bias Surface brightness limits the study of galaxy structure evolution in two major ways. First, galaxies do not have uniform surface brightness over their

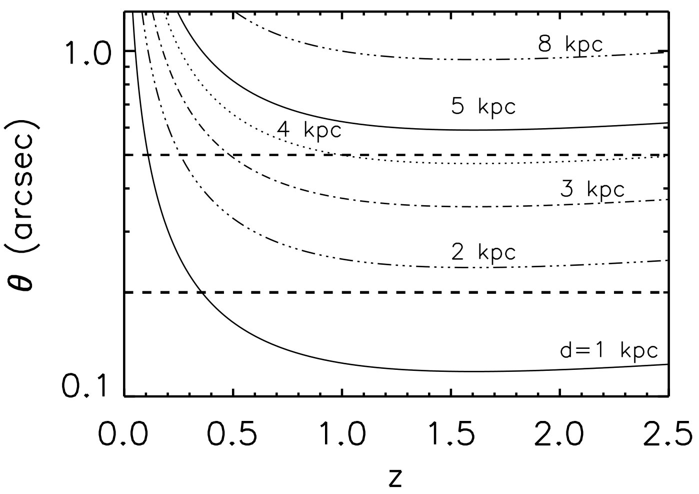

Figure 2: Angular size as a function of redshift for various linear sizes. The dark dashed line at $\theta = 0.5''$ indicates the limit of the Subaru angular resolution, and thus the minimum size of the resolvable structure at each redshift. The dashed line at $\theta = 0.2''$ indicates the Suprime-Cam pixel size.

entire extent. The second effect, cosmological surface brightness dimming, worsens the bias introduced by the first effect. Since the Universe is not characterized by Euclidean geometry, surface brightness is not independent of distance as we would expect. Instead, the surface brightness of objects decreases with redshift, proportional to $(1+z)^4$. Since the COSMOS survey has a fixed surface brightness limit and magnitude limit, I will only be able to measure the galaxies' properties which lay above the Subaru image limits. Thus, the distributions of properties that I derive will lack the contribution of low surface brightness (LSB) galaxies, and the properties I measure will only be characteristic of the brightest parts of brighter galaxies. There are several ways of dealing with the bias caused by surface brightness effects, as illustrated by Lilly et al. (1998), Simard et al. (1999), and Shen et al. (2003), and I will choose one of devise a new method.

Angular Resolution of Subaru Telescope Several of the galaxy structure parameters I propose to measure for this study are highly sensitive to angular resolution, as shown by Bershady et al. (2000) and Lotz et al. (2004). Lotz et al. (2004) find that r_p shifts to higher values at lower resolutions and that C shows systematic offsets greater than $\sim$ 15% at resolution scales less than 500 pc per pixel. However, as shown in Figure 2, the Subaru Suprime-Cam pixel size is $0.2''$, which is more than 500 pc at all the redshifts we will consider. Lotz et al. (2004) also find that A is fairly stable to a spatial resolution of 1 kpc per pixel. However, the Suprime-Cam pixel size corresponds to more than 1 kpc at redshifts greater than $z \sim 0.4$, thus a problem may still exist. Lotz et al. (2004) reports that the observed biases in C and A appear to be a function of Hubble type, so I may be able to remove the effects from the data.

We will also have to account for the fact that the limiting angular resolution corresponds to increasingly large linear sizes at redshifts past $z \sim 0.1$. This can be accomplished by re-binning the Subaru images of lower-redshift galaxies so that the linear resolution then corresponds to that of the highest redshift bin.

Analysis of Rest-frame B Morphology It is well known that the optical appearance of a galaxy is strongly dependent on the wavelength used for observation. While we have chosen the rest-frame B to carry out our study so that our results may be compared more easily to previous studies, the rest frame near-infrared bands (e.g. K) show a better representation of the total stellar mass of galaxies. However, at redshifts above $z \sim 0.5$, the rest-frame near-IR is shifted further into the infrared, where we do not yet have detectors with high enough resolution to carry out such morphological studies of faint objects (the best resolution of *Spitzer* is $1.2''$ at 3.5μm). In addition, the COSMOS survey does not yet possess high-enough quality imaging near $\sim 1\mu$m to carry out morphological analyses out to $z \sim 1$ in the rest-frame R. At any rate, Lotz et al. (2004) conclude that the morphological differences between bands are not very substantial for most normal galaxies observed redward of rest-frame $\sim 3500 - 4000$ Å. Also, B-band is preferable over the near-ultraviolet (NUV) bands, since nearby galaxies appear more irregular and patchy because the rest-frame NUV is biased towards highlighting regions of very recent star formation.

Survey Incompleteness The completeness limit at any level has not yet been measured for the COSMOS data set. Since the completeness limit is based on limiting magnitude, the completeness level for galaxies of different angular sizes will be different. To account for this, we must only make robust conclusions based on galaxies that are part of the most complete sample.

Cosmic Variance While the COSMOS survey covers one of the largest-ever observed contiguous volumes at high redshift, the possibility of obtaining non-representative results due to cosmic variance will remain present to approximately $z \sim 0.7$. There is little that can be done to correct the results for this effect, without knowing the specific clustering properties of the populations we are looking at.

5 SUMMARY

Using Subaru imaging from the COSMOS survey, I will examine the fundamental galaxy properties M_B, $U - B$, r_p, r_h, C, A, and B/D, and evaluate luminous galaxy density in relation to galaxy number density and dark matter halo masses obtained from cosmic shear studies, to study how a galaxy's structural parameters evolve with redshift and environment. My study will be significantly affected by biases due to surface brightness dimming, the angular resolution of the Subaru telescope, and use of the rest-frame B-band to compare galaxy morphology; however, I intend to minimize the effects of biases on my conclusions by applying size and surface brightness cutoffs, minimum-redshift cutoffs, and corrections for known systematic effects.

6 TIMELINE

I can devote my time to this project starting at the current moment. The paper I wrote with my adviser on CO in high-z QSOs is currently in press, and thus requires little attention. Hence, my general plan for completing the study proposed here is as follows:

Summer 2004 – Fall 2004 I will spend 6 months developing measuring and analysis techniques on a small part of the COSMOS field, and perhaps nearby galaxies as well.

Winter 2004/5 – Spring 2005 I will spend approximately 1 month (tentative estimate) measuring each parameter for galaxies in the chosen redshift bins over the full field of the COSMOS survey.

Summer 2005 Local environments will be defined to galaxies in the sample, and data analysis to determine trends as functions of redshift and environment will begin.

Fall 2005 I will continue analyzing the data sample and hopefully submit some papers on the work. I also intend to apply for postdoctoral positions during this time.

Winter 2006 – Spring 2006 I will write and defend my thesis.

If it is deemed necessary to carry out this study using spectroscopic redshifts, my thesis can be extended into a sixth year. The extra time is necessary to allow for the collection of the VLT redshift data, which will occur over a period of at least 2 years (and thus be ready at the end of my fifth year).

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