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FORMING YOUNG BULGES WITHIN EXISTING DISKS: STATISTICAL EVIDENCE FOR EXTERNAL DRIVERS

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ABSTRACT

Contrary to traditional models of galaxy formation, recent observations suggest that some bulges form within preexisting disk galaxies. Such late-epoch bulge formation within disks seems to be linked to disk gas inflow and central star formation, caused by either internal secular processes or galaxy mergers and interactions. We identify a population of galaxies likely to be experiencing active bulge growth within disks, using the criterion that the color within the half-light radius is bluer than the outer disk color. Such blue-centered galaxies make up more than 10% of star-forming disk galaxies within the Nearby Field Galaxy Survey, a broad survey designed to represent the natural diversity of the low-*z* galaxy population over a wide range of luminosities and environments. Blue-centered galaxies correlate at 99% confidence with morphological peculiarities suggestive of minor mergers and interactions. From this and other evidence, we argue that external drivers rather than internal secular processes probably account for the majority of blue-centered galaxies. We go on to discuss quantitative plausibility arguments indicating that blue-centered evolutionary phases may represent an important mode of bulge growth for most disk galaxies, leading to significant changes in bulge-to-disk ratio without destroying disks. If this view is correct, bulge growth within disks may be a natural consequence of the repeated galaxy mergers and interactions inherent in hierarchical galaxy formation.

Key words: galaxies: bulges — galaxies: evolution — galaxies: interactions — galaxies: starburst

1. INTRODUCTION

Traditional wisdom holds that galaxy bulges are old, red, and spheroidal. In this view, bulges are essentially tiny elliptical galaxies that formed early on via either primordial collapse or hierarchical mergers (e.g., Eggen et al. 1962; Kauffmann 1996). The fact that we call these small spheroids "bulges," according to this picture, simply reflects the fact that they later accreted disks.

However, bulges can also be young, blue, and disky. Some bulges display offsets from the Faber-Jackson relation (Faber & Jackson 1976) that are indicative of youthful mass-to-light ratios or disky kinematics (Kormendy & Illingworth 1983; Kormendy 1993). Studies of bulge colors suggest younger ages and/or lower metallicities for late-type galaxy bulges compared with early-type galaxy bulges (Peletier et al. 1999; Carollo et al. 2001) and for bulges compared with elliptical galaxies (Ellis et al. 2001). Bulge colors and inner disk colors correlate closely, hinting at connected formation histories (Peletier & Balcells 1996). Late-type galaxy bulges tend to have exponential rather than $r^{1/4}$-law profiles (e.g., Andredakis et al. 1995), with bulge scale lengths possibly linked to outer disk scale lengths (Courteau et al. 1996; MacArthur et al. 2003, and references therein). Prugniel et al. (2001) find that the Mg_2 index for Sa–Sc bulges correlates better with the outer disk rotation velocity than with the bulge velocity dispersion.

This body of evidence implies that many bulges probably formed or grew substantially at late epochs, evolving both within and together with preexisting disks ("in situ" bulge formation). Two possible scenarios for in situ bulge formation exist. One possibility is internal secular evolution driven by bar instabilities or other nonaxisymmetric distortions, which can cause disk gas inflow, central star formation that enhances the bulge-to-disk ratio, and vertical resonances that diffuse disk stars into the bulge (e.g., Pfenniger & Norman 1990; Friedli & Benz 1993). Alternatively, the same phenomena—nonaxisymmetric distortions, disk gas inflow, and central star formation—can be triggered by neighbor interactions or minor mergers (e.g., Mihos & Hernquist 1994; Steinmetz & Navarro 2002). Even a 10 times lower mass companion can trigger disk gas inflow far disproportionate to the perturber's mass (Hernquist & Mihos 1995). Accretion of small companions can also contribute to in situ bulge growth directly (e.g., Walker et al. 1996; Aguerri et al. 2001). In studies of individual galaxies and nonstatistical samples, internally and externally driven scenarios for in situ bulge growth are virtually completely degenerate. One can rarely rule out faint companions over a wide field, and evidence for minor mergers is even more difficult to detect and interpret.

In this paper we focus on a class of galaxies likely to be currently building bulges via in situ mechanisms, and we attempt to resolve the internal/external trigger degeneracy for these galaxies by statistical means. We identify likely examples of in situ bulge growth by a purely operational criterion adapted from Jansen et al. (2000b, hereafter J00): we look for galaxies in which the color within the half-light radius is bluer than the outer disk color. In such "blue-centered" galaxies, newly formed stars dominate the central colors and may plausibly be changing the concentration index and bulge-to-disk ratio, through both temporary decreases in central stellar mass-to-light ratio and permanent buildup of stellar mass at the center (Schweizer 1990; Wyse et al. 1997; Barton Gillespie, Geller, & Kenyon 2003). The blue-center criterion allows us to examine strongly evolving systems that may contain bars, merger debris, or other unrelaxed structures that

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preclude reliable bulge-to-disk decomposition. We show that the spatial scales of star formation in these objects are consistent with bulge growth.

To determine the frequency and physical drivers of blue-centered galaxies in the general galaxy population, we examine their distribution within the Nearby Field Galaxy Survey (NFGS, Jansen et al. 2000a; J00; Kannappan 2001), a statistically representative sample of low-redshift galaxies spanning all Hubble types over a wide range of luminosities and environments. Blue-centered galaxies make up greater than 10% of star-forming disk galaxies brighter than $M_B = -17.5$ in the NFGS, and they occur with increasing frequency at lower luminosities (Tully et al. 1996; J00). Based on independent, uniform morphological peculiarity classifications for the survey, we will argue that external triggers probably account for the majority of blue-centered galaxies in the NFGS. Uniform but shallow companion data support the same result, with some interpretive ambiguity. This analysis extends previous work linking galaxy encounters to starbursts and central star formation (e.g., Larson & Tinsley 1978; Kennicutt & Keel 1984; Keel et al. 1985; Schweizer 1990; Barton et al. 2000; Barton Gillespie et al. 2003) in that we assess how often central star formation can be traced to galaxy encounters, as opposed to other processes at work in the general galaxy population. Of course, we consider only a special class of central star formation, intense and widespread enough to cause a blue center. The blue-center criterion is not sensitive to small-scale nuclear star formation, star formation on top of very red underlying populations, or central star formation surrounded by comparable amounts of disk star formation. Nonetheless, both the abundance of blue-centered galaxies and the intensity and extent of their central star formation suggest that understanding these galaxies may be important to understanding the phenomenon of in situ bulge growth.

The remainder of this paper is organized as follows. In § 2 we briefly describe the Nearby Field Galaxy Survey, as well as a second sample, the Close Pairs Survey (Barton et al. 2000), which we use for further analysis of blue-centered galaxies with companions. In § 3 we define the outer-minus-inner color difference $\Delta(B-R)$, discuss $\Delta(B-R)$ trends with luminosity and morphology, and summarize the properties of blue-centered galaxies within the NFGS. In § 4 we present statistical correlations between blue-centered galaxies [as well as $\Delta(B-R)$] and factors that may indicate external disturbance, i.e., morphological peculiarities and close companions. In § 5 we present a series of quantitative plausibility arguments to support the suggestion that blue-centered phases represent an important mode of in situ bulge growth. Finally, in § 6 we discuss open questions raised by these results regarding the relationship of blue-centered galaxies to the phenomenon of disky bulges and to the paradigm of hierarchical galaxy formation. We summarize our results in § 7.

2. SURVEY DATA

The Nearby Field Galaxy Survey is ideal for this analysis because it was designed to provide a statistically representative sample of the general galaxy population, without explicit selection bias in color, morphology, or any other galaxy property (J00). Imaging, spectrophotometry, and kinematic data for the NFGS come from J00, Jansen et al. (2000a), and Kannappan (2001), respectively. The 196 galaxies in the NFGS were drawn from the CfA 1 redshift survey (Huchra et al. 1983) in numbers roughly proportional to the local galaxy luminosity function and span the full range of Hubble types and environments (with the exclusion of the Virgo Cluster to avoid overrepresentation of cluster galaxies). However, a key point for the analysis in this paper is the fact that the properties of the NFGS do not reflect those of a flux-limited sample. More luminous galaxies were selected at progressively larger distances (as described in detail in J00), such that all apparent magnitudes m_Z fall in a very narrow range 14–14.5, set by the CfA 1 Survey magnitude limit (where m_Z, the Zwicky magnitude, is similar to a B-band magnitude). In turn, the CfA 1 survey is a subset of the Updated Zwicky Catalog (UZC, Falco et al. 1999), which is an edited and updated version of the CfA 2 redshift survey, with magnitude limit $m_Z = 15.5$. Therefore, the UZC allows us to perform systematic searches for companions to NFGS galaxies down to ~1 mag fainter than the primary. This type of search avoids distance-dependent sampling biases: rather than searching for companions down to a specified absolute magnitude, we search for companions down to ~1 mag fainter than the primary, regardless of primary luminosity or redshift. Physically, such a search is sensible, as the detection threshold reflects an approximately constant interaction mass ratio, regardless of absolute mass scale.

Unfortunately, as we will see in § 4.1, many of the companions relevant to blue-centered galaxies may be too faint, or too closely blended, to be separately cataloged in the UZC. To detect disturbances from small companions or mergers already in progress, we use the uniform set of morphological peculiarity flags defined for the NFGS by Kannappan et al. (2002). These flags do not imply a type Pec classification. To avoid confusion on this point, we group both type Im and type Pec galaxies under type Irr in this paper. This redefinition is incidental, because, except for a brief look at the full NFGS in § 3, we will focus most of our attention on a sample that excludes nearly all type Irr galaxies via a magnitude cut at $M_B = -17.5$.

We also draw on a second survey, the 191 galaxy Close Pairs Survey of Barton et al. (2000), to supplement our analysis of blue-centered galaxies known to have close companions. The Close Pairs Survey was selected from the CfA 2 redshift survey (Geller & Huchra 1989) as a statistical sample of galaxy pairs with line-of-sight velocity separation $\Delta V < 1000$ km s^{-1} and projected spatial separation $\Delta X \lesssim 100$ kpc (Barton et al. 2000, the ΔX limit differs from the original reference because we have recomputed all distances as discussed below). Unlike the NFGS, the Close Pairs Survey reflects the inherent luminosity distribution of its magnitude-limited parent survey. Morphological types for the Close Pairs Survey are based on independent estimates by each of us, using the NFGS as a common calibration sample.[4]

All magnitudes and distances in this paper are computed using $H_0 = 75$ km s^{-1} Mpc^{-1} , with a correction for Virgocentric infall based on the model of (see J00) Kraan-Korteweg, Sandage, & Tammann (1984). We use Galactic extinction corrections derived from Schlegel et al. (1998) for both surveys, and we quote magnitudes without internal extinction corrections except where otherwise indicated. We have checked that adding internal extinction corrections does not influence our results.

3. CHARACTERIZING BLUE-CENTERED GALAXIES

Figure 1 shows the images and surface brightness profiles for all blue-centered galaxies brighter than $M_B = -17.5$ in the

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[4] We have reclassified one NFGS galaxy, A11332+3536, from S0 to SB0/a.

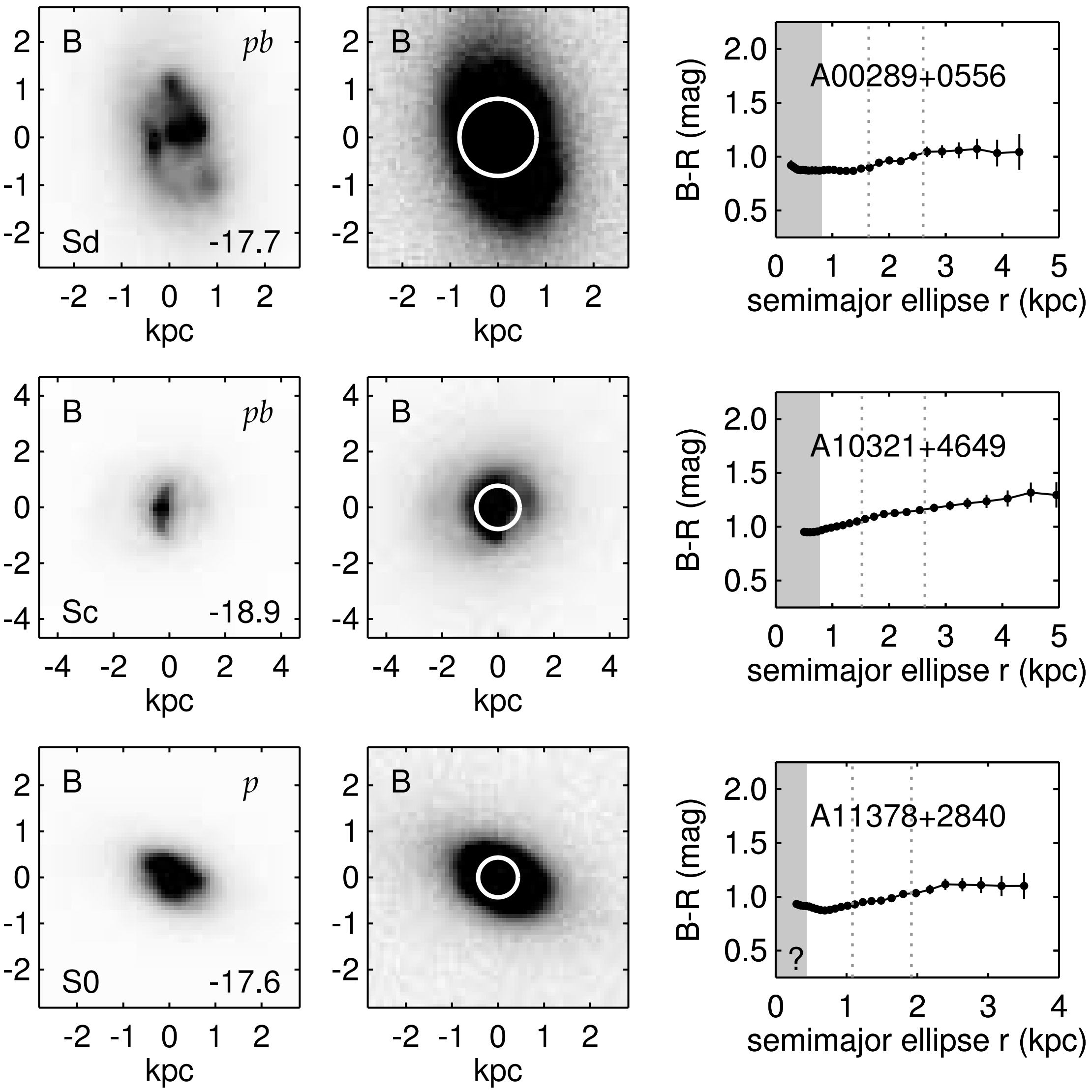

Fig. 1.—Images and radial color profiles for the 11 blue-centered galaxies brighter than $M_B = -17.5$ in the NFGS. Images are shown at two different contrast settings except for NGC 5541, for which we show similar contrast settings in *B* and *K*. Optical data come from J00, and *K*-band data come from the 2MASS All-Sky Data Release postage stamp server. Italic labels *u*, *p*, and *b* indicate close companions in the UZC, morphological peculiarity flags, and bars, respectively. Some galaxies show non-UZC companions, but these do not receive a *u* label. All distances are in kiloparsecs, with radii in the color profiles expressed as major axis distances. Vertical dashed lines mark the half-light and 75%-light radii in each color profile. Central colors influenced by seeing effects are not plotted. The shaded regions of the color profiles and the white circles on the images show the bulge half-light regions one might plausibly expect for the eventual relaxed bulge+disk systems, assuming minimal change in the outer galaxy light profiles (see discussion in § 5.1). Question marks in some of the shaded regions indicate uncertain estimates.

NFGS. We identify these galaxies by the criterion $\Delta(B-R) > 0$, where the color difference $\Delta(B-R)$ equals the outer disk color (from the half-light radius r_e to the 75%-light radius) minus the central color (averaged within r_e). Based on simulated measurements of $\Delta(B-R)$ for model galaxies, this definition of $\Delta(B-R)$ recovers the disk-minus-bulge color difference with less sensitivity to variations in bulge-to-disk ratio than the definition of $\Delta(B-R)$ used by J00. We exclude galaxies with formal errors in $\Delta(B-R) > 0.15$ mag, as well as galaxies with Seyfert 1 or BL Lac nuclei, for which we cannot measure the color of the underlying stellar population (Fig. 2). Typical errors in $\Delta(B-R)$ are $\sim$0.05 mag.

Figure 2 displays the luminosity and morphology distribution of blue-centered galaxies within the NFGS as a whole. Blue-centered galaxies become more common at lower luminosities (Tully et al. 1996; J00). The NFGS shows a natural deficit of intermediate types at low luminosities, reflecting a genuine trend in the general galaxy population, but within this trend, blue-centered galaxies show no preferred morphology. A two-sided K-S test on the morphology distributions for blue-centered and non–blue-centered galaxies in the range $-17.5 < M_B < -20$ yields 58% probability that they were drawn from the same parent distribution, confirming that there is no correlation.

For the remainder of this paper, we restrict our analysis to galaxies brighter than $M_B = -17.5$. This limit excludes dwarf galaxies for which measurements of $\Delta(B-R)$ might be dominated by a few stochastically distributed star formation regions (J00). Relaxing this limit to include fainter galaxies yields stronger statistical results but complicates their interpretation.

The low luminosities of blue-centered galaxies reflect a more general correlation between the continuous parameter $\Delta(B-R)$ and luminosity, followed by the entire population of

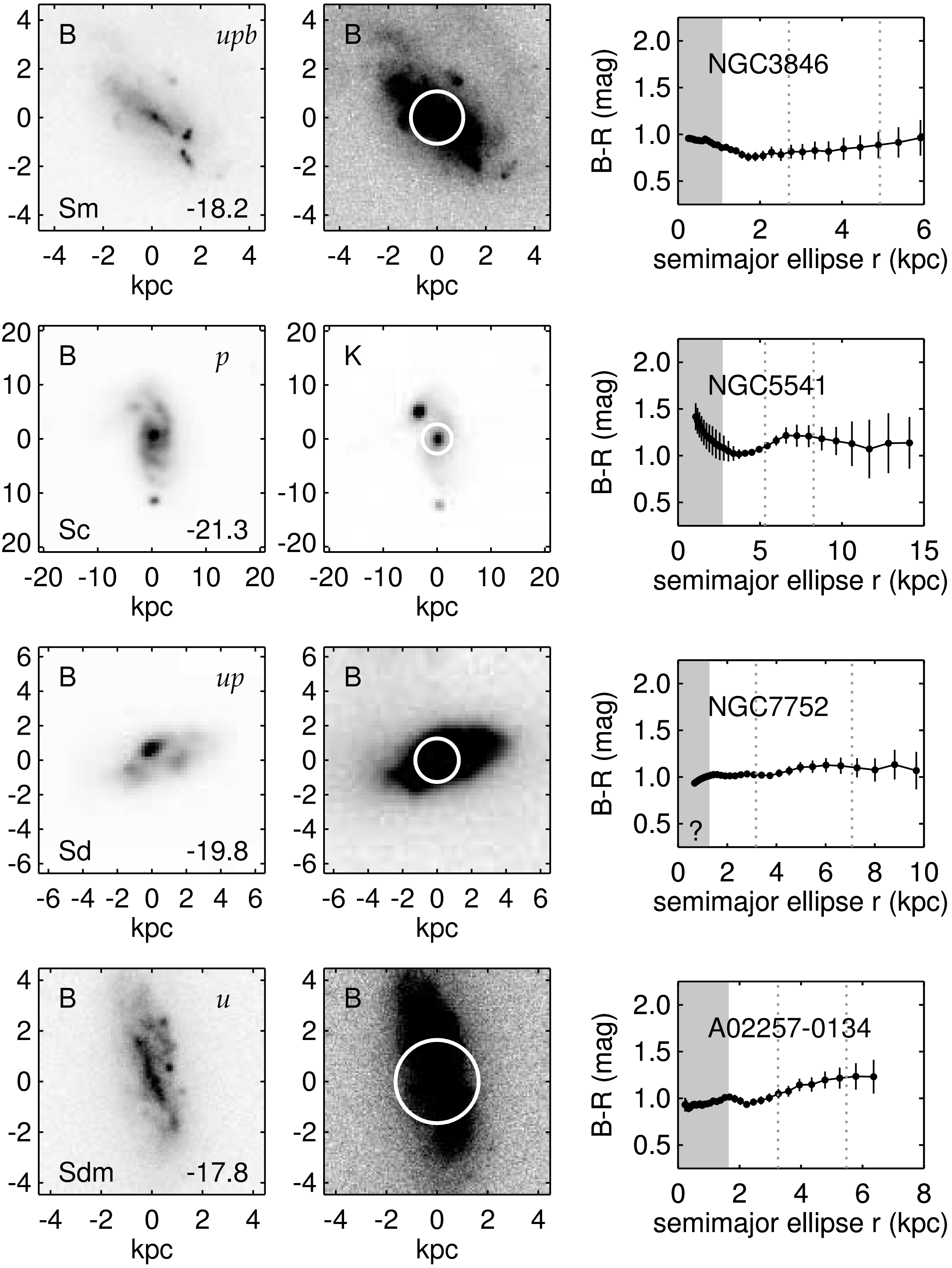

FIG. 1.—*Continued*

star-forming[5] disk galaxies (Fig. 3*a*, Spearman rank test probability of no correlation 1×10^{-4}). While we have chosen the $\Delta(B-R) > 0$ criterion as a conservative way to identify galaxies whose central concentrations are growing, some of the almost–blue-centered outliers at the bright end of the luminosity-$\Delta(B-R)$ relation may also be experiencing preferential central growth, diluted in color by the redness of a large preexisting bulge. In fact, blue-centered galaxies lie at one extreme of an approximately Gaussian distribution of $\Delta(B-R)$ values for star-forming disk galaxies (Fig. 3*b*). Clearly, the processes occurring in blue-centered galaxies may also affect non–blue-centered galaxies to various degrees. We return to this point in §§ 4.1 and 5.4.

As seen in Figures 2 and 3, nearly all blue-centered galaxies in the NFGS are star-forming disk galaxies. This

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[5] We identify galaxies as star-forming if the high-resolution spectra from the NFGS kinematic database (Kannappan 2001) show emission lines beyond the nucleus. Because of lower resolution or missing data, not all of these galaxies are listed as having emission in the NFGS spectrophotometric database (Jansen et al. 2000a).

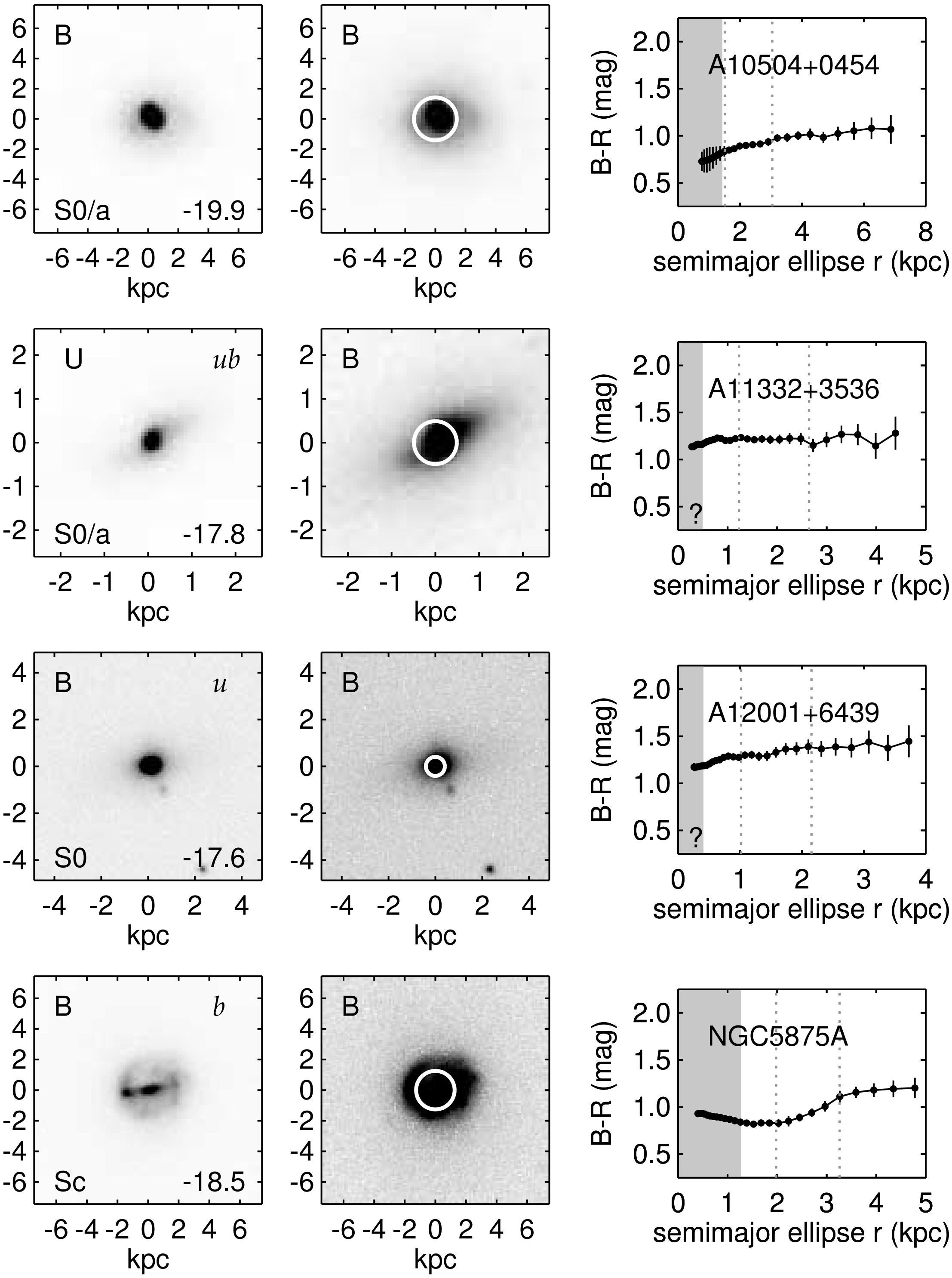

Fig. 1.—*Continued*

fact is unsurprising, as nearly all NFGS galaxies fainter than $M_B = -20$ are star-forming disk galaxies. Most blue-centered galaxies are also starburst galaxies: the 11 in our NFGS sample have median central and global Hα equivalent widths of 37 and 29 Å, respectively.[6] Individual central equivalent widths reach as high as ~130 Å. Only one galaxy, NGC 5541, has a central EW(Hα) below ~15 Å in emission; this galaxy is also exceptional among blue-centered galaxies for its high luminosity, and its blue-centered status may partly reflect blending with a smaller companion (see the Appendix). Because we have taken an objective, operational approach to identifying blue-centered galaxies, we choose not to reject NGC 5541 from our sample. However, we have verified that all of our results

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[6] Central equivalent widths were extracted from a fixed $3'' \times 7''$ aperture, while global equivalent widths were obtained by scanning the slit across the galaxy (Jansen et al. 2000a).

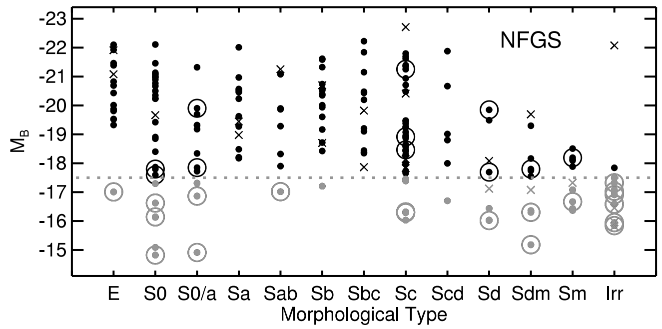

FIG. 2.— Distribution of absolute magnitude and morphological type for the full NFGS sample. Circles identify blue-centered galaxies. The dashed line shows the lower luminosity cutoff for the sample of 133 galaxies analyzed in this paper (§ 3). Gray symbols mark galaxies excluded by the luminosity cut, while crosses mark galaxies excluded from analysis because of large errors in $\Delta(B-R)$ or dominant AGNs (§ 3).

hold with comparable statistical significance if this galaxy is excluded.

4. WHAT DRIVES THE STAR FORMATION?

4.1. *Local Environment*

In this section we consider how blue-centered galaxies, as well as the continuous parameter $\Delta(B-R)$, correlate with possible evidence for interactions and mergers. We expect that interactions *can* produce blue-centered galaxies, as numerous studies have demonstrated that galaxy encounters can enhance central star formation (e.g., Keel et al. 1985; Barton et al. 2000). Confirming this expectation, Figure 4 shows that blue-centered galaxies in the Close Pairs Survey tend to have closer companions than do their non–blue-centered counterparts. Also, blue-centered galaxies are roughly twice as common in the Close Pairs Survey as in the NFGS (∼20% vs. ∼10% of star-forming disk galaxies brighter than $M_B = -17.5$) despite the top-heavy luminosity distribution of the Close Pairs Survey (Fig. 5). However, these results do not address the question of whether galaxy interactions are the *primary* cause of blue-centered galaxies in the general galaxy population or just one possible cause.

To understand the source of blue-centered galaxies in the general galaxy population, we turn to the NFGS. Our analysis considers two types of evidence for interactions and mergers: morphological peculiarities and close companions. We use the uniform peculiarity flags that were defined for the NFGS by Kannappan et al. (2002) in the context of identifying galaxies that might be considered disturbed from the point of view of analyzing the Tully-Fisher relation (Tully & Fisher 1977). These flags may indicate multiple nuclei, likely interacting companions, tidal tails or debris, or asymmetries not readily attributable to late-type morphology. Such features often provide the only direct evidence of a merger origin for starburst activity (e.g., Schweizer & Seitzer 1992). Although inevitably subjective, the NFGS peculiarity flags combine the independent judgement of two classifiers, as well as notes in the literature, and reflect a uniform peculiarity threshold. Unfortunately, compared with the human eye, quantitative measures such as the photometric asymmetry index of Abraham et al. (1996) do not perform well in detecting minor disturbances associated with small-companion interactions.[7] All of the blue-centered galaxies in Figure 1, including NGC 5541, have unexceptional photometric asymmetries (as measured by Jansen 2000 following the methods of Abraham et al.). In fact, within the NFGS, only a handful of extreme major merger remnants are outliers in plots of photometric asymmetry versus color or luminosity, consistent with the results of Conselice (2003), who finds unusual asymmetries only for severely disturbed Antennae-like systems.

We identify companions within 300 kpc and 300 km s^{-1} of each NFGS galaxy using the UZC (§ 2). The value 300 km s^{-1} was chosen because most blue-centered galaxies in the Close

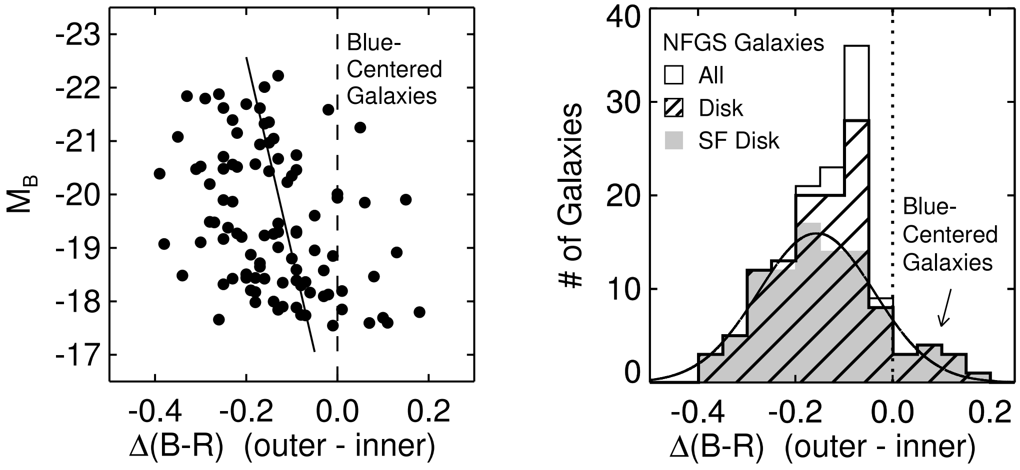

FIG. 3*a*

FIG. 3*b*

FIG. 3.—Luminosity dependence of $\Delta(B-R)$ for star-forming disk galaxies in the NFGS. The line is a least-squares inverse fit [$\Delta(B-R)$ as a function of luminosity] with equation $M_B = -15.2 + 30.7 \times \Delta(B-R)$. (*b*) Distribution of $\Delta(B-R)$ for NFGS galaxies of all morphological types (*open histogram*), with subdistributions for disk galaxies (*hashed*) and star-forming disk galaxies (*shaded*). The Gaussian fit to the star-forming disk galaxy sample has mean −0.16 and $\sigma = 0.12$ mag. Both panels and all remaining figures exclude galaxies fainter than $M_B = -17.5$ and galaxies marked with a cross in Fig. 2.

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[7] Kinematic asymmetries may be a somewhat more powerful tool (e.g., Kannappan 2001, 2002; Kannappan & Barton 2003), but separating interaction-induced kinematic asymmetries from other effects requires highly inclined galaxies with spatially well-sampled rotation curves.

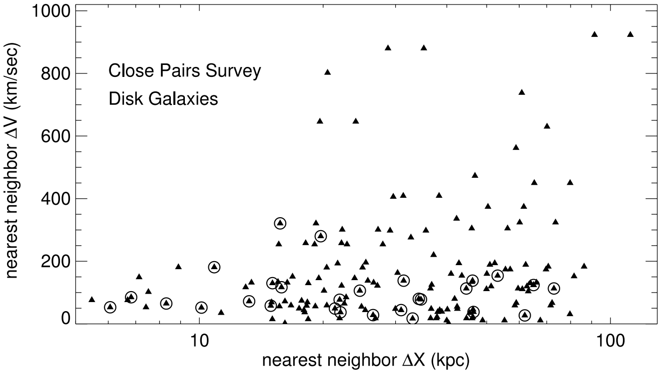

Fig. 4.—Projected distance and line-of-sight velocity separation to the nearest neighbor for galaxies in the Close Pairs Survey. Blue-centered galaxies are circled. Separate K-S tests on ΔV and ΔX indicate that blue-centered galaxies tend to have smaller neighbor separations than non–blue-centered galaxies at 97% and 95% confidence, respectively.

Pairs Survey have companion separations $\lesssim 300$ km s^{-1} (Fig. 4). Assuming a starburst timescale of ∼1 Gyr, we infer that a companion as distant as ∼300 kpc away might have caused the observed starburst in a blue-centered galaxy. The UZC includes galaxies as much as 1 mag fainter than the CfA 1 redshift survey, the parent survey of the NFGS. However, we find that several blue-centered galaxies have possible companions that are too close or too faint to be cataloged separately in the UZC; these companions do not enter in our statistical analysis of companions, but we discuss them further below. Our results suggest that a much deeper (future) catalog will be necessary to detect the majority of relevant companions and perform decisive statistical tests.

Blue-centered galaxies with morphological peculiarities or UZC companions are labeled *p* and *u* in Figure 1. From simple binomial statistics, peculiarities and UZC companions are overabundant among blue-centered galaxies at 99% and 95% confidence, respectively, compared with star-forming disk galaxies in general (Table 1). Combining the two types of evidence, nine of 11 blue-centered galaxies show either a peculiarity or a UZC companion or both, indicating a correlation at 99.9% confidence.

Similar but weaker correlations emerge if we treat $\Delta(B-R)$ as a continuous parameter. Figure 6 plots the $\Delta(B-R)$ distributions for star-forming disk galaxies (*a*) with and without strong peculiarities and (*b*) with and without UZC companions. Kolmogorov-Smirnov tests indicate a 1.6% probability that peculiar and nonpeculiar galaxies have the same parent $\Delta(B-R)$ distribution and a 12% probability that galaxies with and without UZC companions have the same parent $\Delta(B-R)$ distribution.

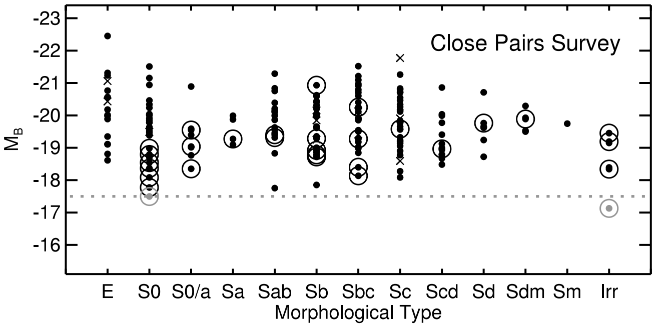

Fig. 5.—Luminosity and morphology distribution for the full Close Pairs Survey. Circles identify blue-centered galaxies. Crosses mark galaxies excluded from analysis because of large photometric errors or dominant AGNs. The dashed line shows the lower luminosity cutoff for the sample analyzed in this paper (§ 3). Gray symbols mark galaxies excluded by the luminosity cut.

The peculiarity-$\Delta(B-R)$ correlation is independent of both the UZC companion–$\Delta(B-R)$ correlation and the luminosity-$\Delta(B-R)$ correlation discussed in § 3. If anything, Figure 7*a* shows a slight bias *against* identifying strong peculiarities in low-luminosity galaxies, presumably because many low-luminosity galaxies have late-type morphologies that make peculiarities less obvious. Furthermore, the peculiarity correlation actually strengthens if we define a luminosity-corrected parameter, $\Delta(B-R)_{\mathrm{corr}}$, equal to the residuals from the relation in Figure 3*a*. Physically, the introduction of $\Delta(B-R)_{\mathrm{corr}}$ is motivated by the possibility that brighter galaxies may more often have large preexisting red bulges or bars that dilute the color difference $\Delta(B-R)$ even in the presence of preferential central star formation. Peculiar and nonpeculiar galaxies differ in their $\Delta(B-R)_{\mathrm{corr}}$ distributions at 99.5% confidence in a K-S test (Fig. 8).

In contrast, the presence or absence of a UZC companion does not clearly affect the distribution of $\Delta(B-R)_{\mathrm{corr}}$. In fact, the weak correlation between UZC companions and the uncorrected color difference $\Delta(B-R)$ may not be entirely independent of the luminosity-$\Delta(B-R)$ correlation because UZC companions are more common for lower luminosity galaxies (Fig. 7*b*; K-S test confidence = 98%). This result is not unique to the NFGS; we have verified it for the entire UZC.[8] As discussed in § 2, our companion search is not subject to distance-dependent sampling biases. Physically, the UZC companion–luminosity correlation seems to reflect the fact that the galaxy luminosity function cuts off at high luminosities: brighter neighbors are more common for faint primaries than for bright primaries, because faint primaries have a wider range of possible neighbor luminosities within which neighbors *can* be brighter than the primary. These brighter neighbors may well trigger some blue-centered starbursts. However, we suspect that the luminosity-$\Delta(B-R)$ correlation is more fundamental than the UZC companion–$\Delta(B-R)$ correlation, for two reasons: (1) the former is statistically stronger than the latter [although the discrete correlations involving blue-centered galaxies instead of $\Delta(B-R)$ are of comparable, weaker strength]; and (2) the Close Pairs Survey, a sample in which all galaxies have companions, shows a clear luminosity-$\Delta(B-R)$ correlation (as suggested by Fig. 5).

We conclude that the link between morphological peculiarities and blue-centered galaxies is robust, while the link between UZC companions and blue-centered galaxies is not. Most likely, the UZC misses the majority of relevant companions, because they are too faint, too close, or already

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[8] If we select as primaries all UZC galaxies brighter than $B = 14.5$ (i.e., 1 mag above the survey limit), then search for their companions in the full UZC (all the way down to 15.5), we find a K-S test probability of 6.6×10^{-29} that primaries with and without companions share the same underlying luminosity distribution. The subsample with companions clearly includes a higher proportion of lower luminosity primaries, just as for the NFGS in Fig. 7. Furthermore, when we perform a second test considering only fainter companions between 14.5 and 15.5, the K-S result disappears, indicating that the excess companions detected for lower luminosity primaries in the first test are excess *brighter* companions. These results are consistent with the argument that the luminosity-companion correlation is caused by the bright-end cutoff of the luminosity function: as the primary luminosity increases, there is a decrease in the physically allowed range of companion luminosities within which companions can be brighter than the primary.

TABLE 1

Statistical Properties of Blue-centered Galaxies in the NFGS[a]

	Overall			UZC Companion			Morph. Peculiar			UZC Comp. or Pec.			Barred		
Sample[b]	N	$N_{\rm BC}$	f (%)	N^i	$N^i_{\rm BC}$	$p^{\rm bin}$	N^p	$N^p_{\rm BC}$	$p^{\rm bin}$	$N^{i/p}$	$N^{i/p}_{\rm BC}$	$p^{\rm bin}$	$N^{\rm bar}$	$N^{\rm bar}_{\rm BC}$	$p^{\rm bin}$
All galaxies	133	11	8	34	5	0.1	22	6	0.004	49	9	0.003	37	5	0.2
Disk galaxies	120	11	9	26	5	0.07	21	6	0.006	41	9	0.002	37	5	0.2
Faint disks (>-20)	72	10	14	18	5	0.08	12	5	0.02	26	8	0.006	27	5	0.3
SF disks	96	11	11	19	5	0.05	19	6	0.01	32	9	0.001	36	5	0.4

[a] Probabilities p measure the likelihood of no correlation. For N sample galaxies of which N^x have property x, $p^{\rm bin}$ is the probability that $N^x_{\rm BC}$ or more of the $N_{\rm BC}$ blue-centered galaxies could have property x by chance (from the binomial theorem).

[b] Samples are restricted to luminosities brighter than $M_B = -17.5$. In addition, we exclude AGN-dominated galaxies and galaxies with large uncertainty in $\Delta(B-R)$.

merging. Four of the 11 blue-centered galaxies in our sample show evidence of possible close or merging companions that are not listed in the UZC (Appendix: A10504+0454, NGC 3846, 5541, and 5875A). Morphological peculiarities may sometimes indicate the presence of such companions, but not always. Of the four galaxies just mentioned, only two are flagged as clearly peculiar based on NFGS images. For the other two, evidence of a companion relies on new, much higher resolution imaging and infrared color information. In addition, we find that two other blue-centered galaxies whose NFGS images do not reveal peculiarites also show evidence of recent merging, based on kinematic data or again, new much higher resolution imaging (Appendix: A12001+6439 and A11332+3536). While these latter two galaxies actually do have companions in the UZC, they may well be minor merger cases where the UZC companions are incidental.

Overall, we find that every one of our blue-centered galaxies shows some evidence of interactions and mergers, often suggestive of small companion accretion. However, a deep high-resolution survey capable of uniformly detecting the more subtle signs of such encounters does not yet exist, so for the present our statistical claims cannot go beyond what we have shown using UZC companion data and the uniform peculiarity flags derived from the original NFGS images.

4.2. *Global Environment*

On larger scales blue-centered galaxies in the NFGS and the Close Pairs Survey do not seem to favor any particular environment (Fig. 9). A K-S test shows that the environmental density distributions of blue-centered and non–blue-centered galaxies are not statistically different. The majority of blue-centered galaxies we find, like the majority of galaxies in our surveys, are in moderate- to low-density environments. Low-density *global* environments may provide ideal conditions for starbursts to be triggered by *local* interactions: lower speed encounters, more cold gas available to form stars, and later epochs of hierarchical assembly (as found by Grogin & Geller 2000). We note that the S0 and S0/a blue-centered galaxies in our surveys do not reside in dense environments and probably do not reflect cluster processes such as harassment or ram-pressure stripping. Our surveys include relatively few galaxies in the high-density environments where such processes might play a larger role.

4.3. *Bars*

Blue-centered galaxies show only a slight, statistically insignificant excess of bars compared with the general population of star-forming disk galaxies (Table 1). Likewise, the presence of bars does not correlate with $\Delta(B-R)$ or with central or global EW(Hα), except in the broad sense that bars occur predominantly in star-forming disk galaxies. Moreover, we detect no correlation between bars and either local or global environment within the star-forming disk galaxy sample.

These results appear to challenge both the secular and the interaction-driven scenarios for in situ bulge growth, because both scenarios predict bar formation that drives disk gas inflow. However, bar statistics should be interpreted with caution, given the possibly heterogeneous origins of bars, as well as their long lifetimes (e.g., Noguchi 1996; Sellwood 2000). In addition, small-scale bars may be difficult to detect at the $1\farcs5$–$2''$ spatial resolution of the images in Figure 1, and distortions from interactions and minor mergers may make bars difficult to identify.

We also note that although previous studies have shown that bars enhance *nuclear* star formation (see Kennicutt 1998 and references therein), such star formation may have insufficient intensity or spatial extent to influence blue-centered galaxy statistics. It remains an open question whether enhanced central star formation in the general galaxy population is frequently or predominantly associated with bars.

5. BLUE-CENTERED GALAXIES AS AN IMPORTANT MODE OF IN SITU BULGE GROWTH

We have demonstrated that in a statistically representative galaxy sample, most if not all blue-centered galaxies show evidence of interactions and mergers. Here we offer plausibility arguments for the further claim that blue-centered (or almost–blue-centered) phases represent an important mode of in situ bulge growth.

5.1. *Linking Blue Centers to Young Bulges*

Linking central star formation to bulge formation requires a working definition of the word "bulge." We know that many bulges defy the stereotype of smooth, red, $r^{1/4}$-law spheroids. Improved resolution and/or subtraction of the smooth underlying stellar distribution often reveal complex internal structures, such as bars, spiral arms, and knots (Kormendy 1993; Carollo 1999). Sersic $r^{1/n}$-law fits to bulge surface brightness profiles yield n values ranging from the classical $n = 4$ (or even larger) down to $n < 1$ (Andredakis et al. 1995), where $n = 1$ describes an exponential profile. In some cases the basic distinction between bulges and disks may turn out to be an artifact of traditional analysis techniques: Böker et al. (2003) report that late-type galaxies observed with *HST* resolution are equally well fitted with a single Sersic profile as with two

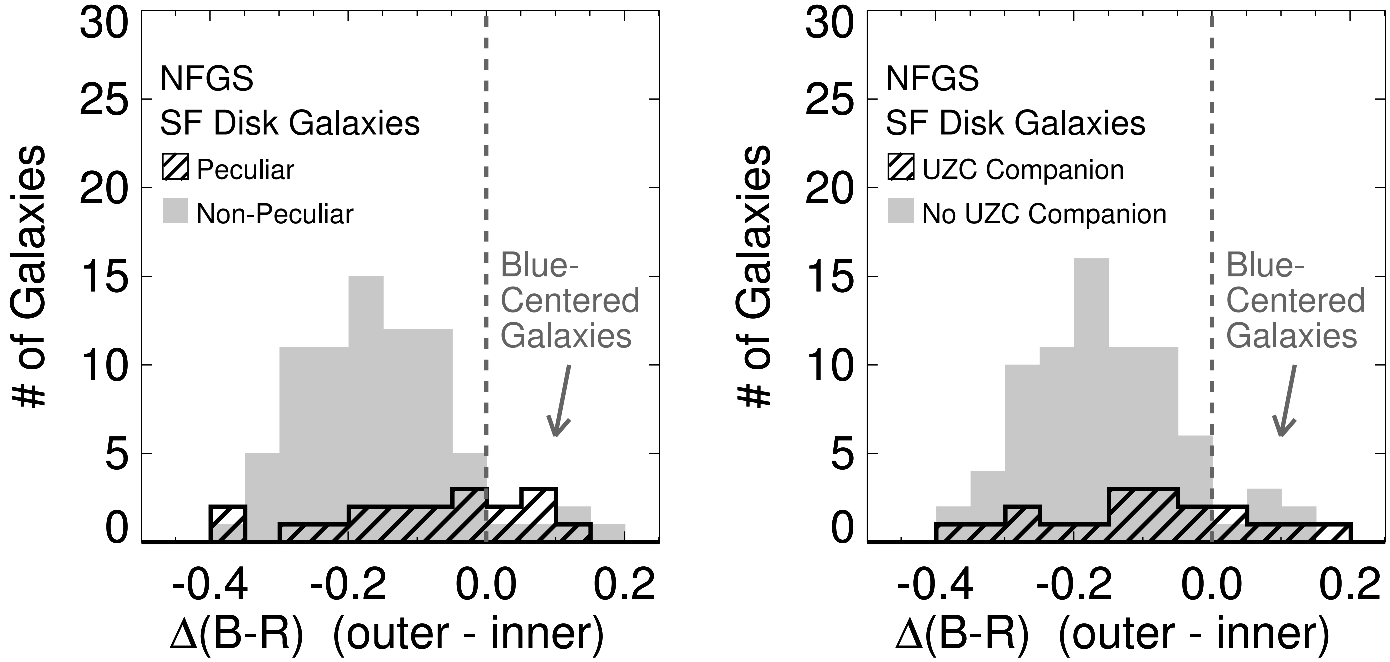

FIG. 6*a*

FIG. 6*b*

FIG. 6.—Distribution of the color difference $\Delta(B-R)$ for star-forming disk galaxies (*a*) with and without morphological peculiarities and (*b*) with and without close companions in the Updated Zwicky Catalog (UZC, Falco et al. 1999).

exponentials. Wyse et al. (1997) offer the practical definition that a bulge is "any light that is in excess of an inward extrapolation of a constant scale-length exponential disk," but even this definition falls short when the surface brightness profile of the outer disk is not well described by a single exponential (e.g., when the profile is disturbed or contains a second disk or shelf).

In light of these arguments, we suggest that any central excess of stars on a spatial scale traditionally associated with bulges may be plausibly described as a bulge or protobulge structure. Even bars, when they have the right spatial scale, may be identified with bulges, as buckled or destroyed bars are expected to evolve into bulge components (e.g., Friedli & Benz 1993). Therefore, a good consistency check on whether

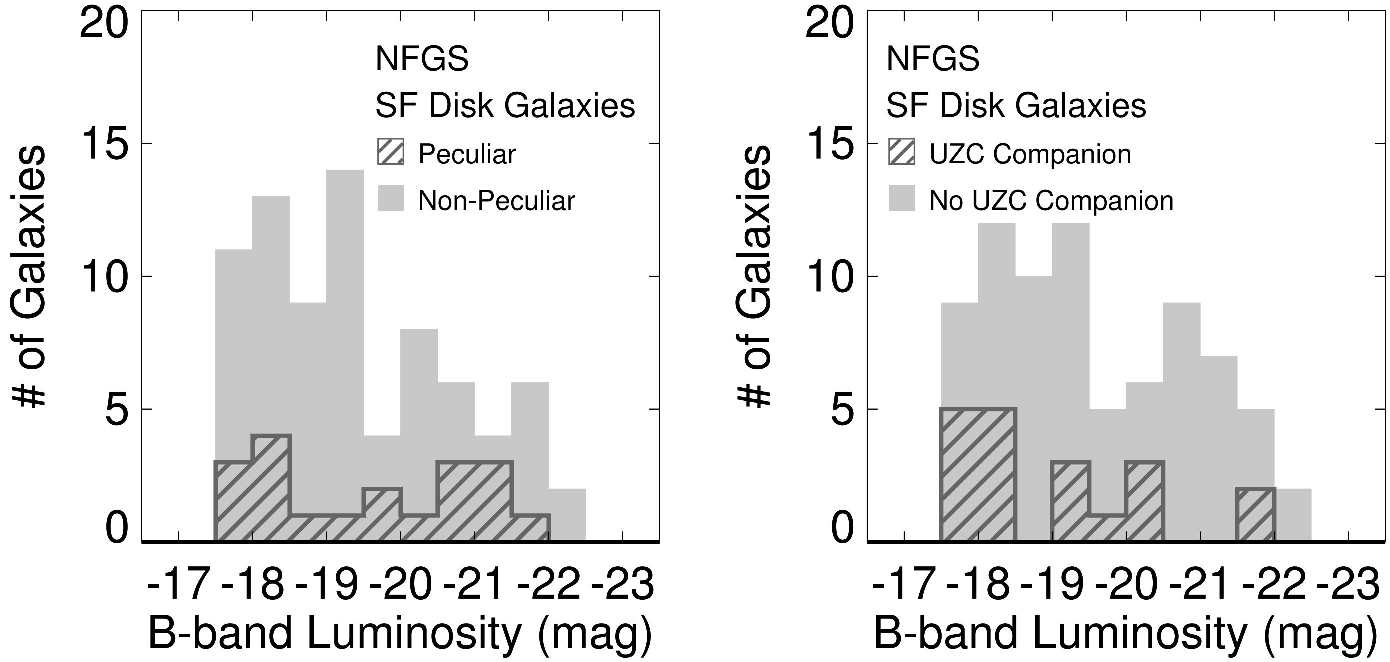

FIG. 7*a*

FIG. 7*b*

FIG. 7.—Luminosity distributions for star-forming disk galaxies (*a*) with and without strong morphological peculiarities and (*b*) with and without close companions in the UZC. Note that the tendency for fainter galaxies to have more companions does not reflect distance-dependent sampling bias, but rather the fact that the luminosity function cuts off at high luminosities (§§ 2 and 4.1).

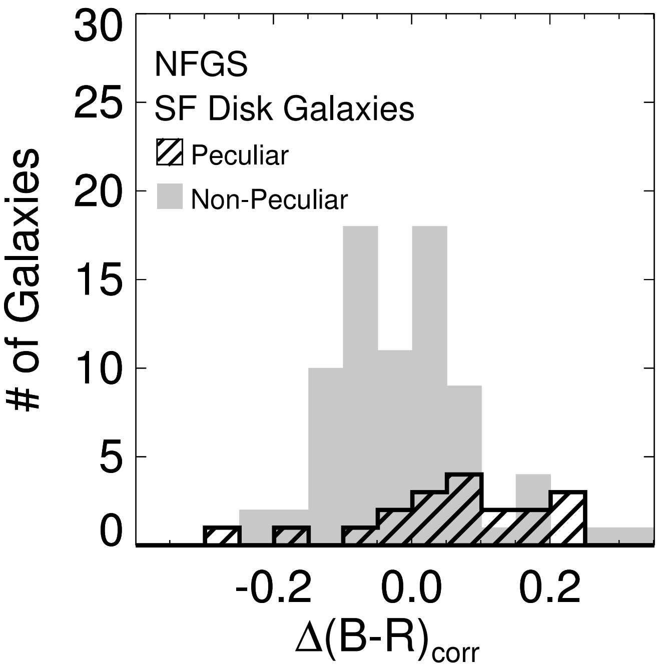

FIG. 8.—Distribution of the luminosity-corrected color difference $\Delta(B-R)_{\rm corr}$ for star-forming disk galaxies with and without morphological peculiarities. $\Delta(B-R)_{\rm corr}$ is defined as the residual in $\Delta(B-R)$ after subtracting the fitted relation shown in Fig. 3*a*.

central star formation implies bulge formation would be to verify that the spatial scale of the star formation corresponds to a typical bulge size scale. Fully formed bulges loosely scale according to $r_e^{\rm bulge} \sim 0.2 r_e^{\rm disk}$ and $r_e^{\rm bulge} \sim 0.1 r_e^{\rm disk}$ for early- and late-type spiral galaxies, respectively, with values up to $r_e^{\rm bulge} \sim 0.4 r_e^{\rm disk}$ observed (Moriondo et al. 1998; Graham 2001; MacArthur et al. 2003). Also, since fully formed bulges and inner disks show evidence of closely related star formation histories (e.g., Peletier & Balcells 1996), the starbursts in blue-centered galaxies may extend to both bulges and inner disks. We therefore adopt the upper envelope of the observations, $r_e^{\rm bulge} = 0.4 r_e^{\rm disk}$, as a plausible estimate of the expected scale of a bulge-building starburst.

The shaded regions of the color profiles in Figure 1 show the regions within $r_e^{\rm bulge} = 0.4 r_e^{\rm disk}$ for the 11 blue-centered galaxies in our analysis. For most galaxies, we measure $r_e^{\rm disk}$ from an exponential fit to the outer disk surface brightness profile. For a few galaxies with ill-defined outer disks (those with a question mark in Fig. 1), we compute $r_e^{\rm bulge}$ using $r_e^{\rm tot}$ rather than $r_e^{\rm disk}$. When this substitution is necessary, the computed $r_e^{\rm bulge}$ is a lower limit.

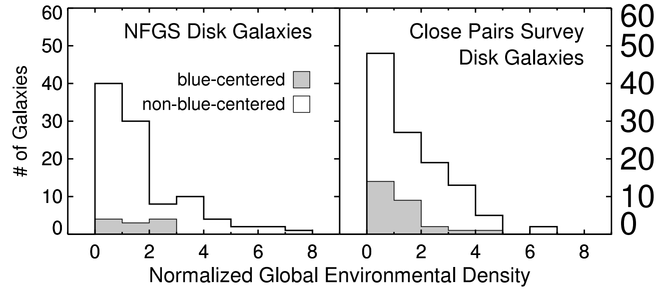

FIG. 9.—Distributions of global environmental density for blue-centered and non–blue-centered galaxies. Densities are expressed in units of the mean density of galaxies brighter than $M_B \sim -17$ smoothed on 6.7 Mpc scales, using code adapted from N. Grogin (Grogin & Geller 1998). In these units the densities of the Virgo and Coma Clusters are ∼4.9 and 7.4, respectively.

Inspection of the color profiles in Figure 1 reveals that in most cases, the shaded regions and the regions of excess blue light correspond reasonably well. (NGC 5541 is a strong exception, possibly for the reasons discussed in § 3.) Quantifying this correspondence is tricky however. To estimate the spatial scale of the excess blue light very approximately, we add the $B-R$ color of the outer disk to the R-band profile and subtract the result from the B-band profile. We then compute the half-light radius $r_e^{\rm blue}$ of the excess blue light. Blue-centered galaxies have a median $r_e^{\rm blue}$ of $\sim 0.5 r_e^{\rm disk}$ (where again we substitute $r_e^{\rm tot}$ for $r_e^{\rm disk}$ for galaxies with ill-defined outer disks, in this case with the effect of overestimating the ratio of $r_e^{\rm blue}$ to $r_e^{\rm disk}$). This value is quite consistent with $r_e^{\rm bulge}$ as estimated above. However, the scatter in $r_e^{\rm blue}$ is large, and we have ignored the presence of underlying disk color gradients, which are highly uncertain for blue-centered galaxies.

Another uncertainty in assessing the starburst scale arises from substructure within the starburst. A few galaxies in Figure 1 show local reddening trends inside the shaded $r_e^{\rm bulge}$ region, superposed on the general trend toward bluer colors with decreasing radius. Others show central blueing in excess of the general trend, and some show more blueing in $U-B$ than in $B-R$ (Fig. 10), perhaps indicating that dust has suppressed the blueing in $B-R$ (although extinction is more severe in U and B than in R, it affects $B-R$ colors more than $U-B$ colors; Gordon et al. 1997). We speculate that this substructure within the starburst color profiles may be related to the differentiation of the bulge and the inner disk via gradients in starburst age, intensity, and/or dust formation. Despite the uncertainty in interpreting such features, we conclude that the starbursts in blue-centered galaxies are plausibly related to bulge formation.

5.2. *Externally Driven Bulge Growth without Disk Destruction*

All of the bulge growth we identify by the blue-center criterion occurs within intact disk galaxies. However, one may

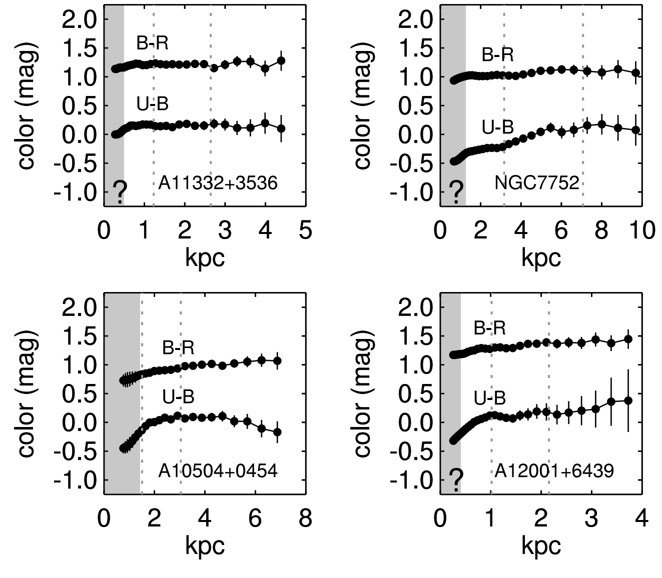

FIG. 10.—Radial color profiles for four blue-centered galaxies that show stronger central blueing in $U-B$ than they do in $B-R$, indicating radial gradients in starburst properties (§ 5.1). Color profiles are annotated as in Fig. 1.

ask whether these galaxies' disks will soon be destroyed by mergers. Of the 11 blue-centered galaxies in Figure 1, only four have a larger neighbor within 300 kpc and 300 km s^{-1}. Only one of these, NGC 7752, appears to be in direct contact with its larger companion. Therefore, major mergers are unlikely for most of these galaxies for at least a few gigayears.[9]

We note that substantial gas inflow and bulge growth do not require large companions. Hernquist & Mihos (1995) find that a 10 : 1 merger can drive up to ~50% of the *larger* galaxy's gas into its center, so that the inflowing gas significantly outweighs the mass of later accreted material. Minor mergers and interactions with small companions have been observed to thicken but not destroy the disks of larger galaxies (e.g., Schwarzkopf & Dettmar 2000). Furthermore, subsequent thin-disk regrowth is likely, occurring through both fresh gas accretion and fall-back of tidal debris (Barnes 2002).

5.3. *Potential for Evolution in Bulge-to-Disk Ratio*

Although the blue colors and large Hα equivalent widths of blue-centered galaxies clearly reveal starburst activity, one may nonetheless ask whether the starbursts are of sufficient intensity to produce noticeable changes in bulge-to-disk ratio. To answer this question carefully would require Hα imaging combined with detailed modeling of the stellar populations and star formation histories of blue-centered galaxies. Such work is in progress and is beyond the scope of this paper. For the moment, we offer a simple plausibility argument for the possibility of significant bulge growth in blue-centered galaxies.

We consider an idealized three-component galaxy with a preexisting disk, a preexisting bulge, and a new bulge component that forms on top of the old bulge during the blue-centered phase. We construct a population synthesis model for each component, treating early (S0–Sb) and late (>Sb) Hubble types separately. The early-type model has an exponential disk, a coeval $r^{1/4}$-law bulge, and a new $r^{1/4}$-law bulge. The late-type model substitutes exponential bulges. The preexisting bulges follow $r_e^{\rm old\ bulge} = 0.2r_e^{\rm disk}$ and $r_e^{\rm old\ bulge} = 0.1r_e^{\rm disk}$ for early- and late-type galaxies, respectively (MacArthur et al. 2003 and references therein), while the new bulges in both models follow $r_e^{\rm new\ bulge} = 0.4r_e^{\rm disk}$ (see discussion in § 5.1).

We use the spectral synthesis models of Bruzual & Charlot (1996; Salpeter IMF, solar metallicity) to generate the stellar populations, adopting exponential star formation histories with a 1 Gyr timescale for the preexisting bulge, a 4 Gyr timescale for the early-type galaxy disk, and a 7 Gyr timescale for the late-type galaxy disk. For the new bulge, we consider two possible burst timescales, 100 Myr and 1 Gyr. The shorter timescale represents a plausible lower limit based on detailed modeling of externally triggered starbursts by Barton Gillespie et al. (2003), while the longer timescale is closer to the dynamical timescale and might encompass two or more subbursts within a realistic encounter. The new bulge starts to form 8 Gyr after the preexisting components. Our models reproduce the average central and outer disk colors of NFGS blue-centered galaxies, yielding $\Delta(B-R)$ values similar to those observed (Fig. 11). We match the effective colors after 4 Gyr of fading to the colors of non–blue-centered galaxies in the NFGS of early and late Hubble types. Just before the new bulges form, the preexisting bulges have bulge-to-total luminosity ratios $B/T \sim 0.2$ and ~0.04 for the early- and late-type models, respectively. During the blue-centered phases, the models generally have appropriate total B/T for early- and late-type galaxies (combining the new+old bulges), although the late-type model with the 100 Myr burst varies rapidly in total B/T from ~0.6 down to ~0.2 just within the brief blue-centered phase.

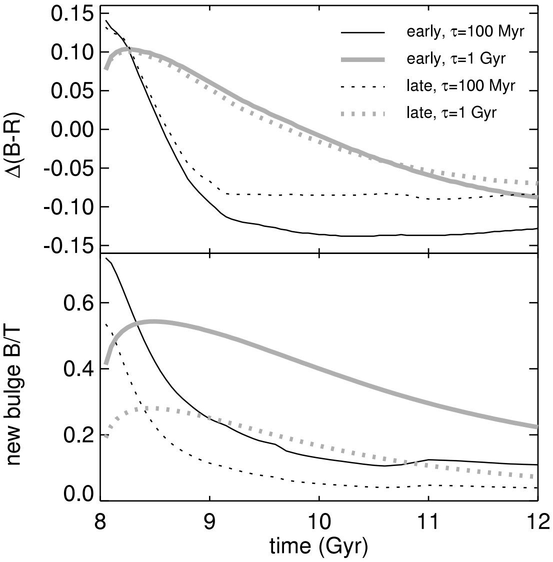

FIG. 11.—Time evolution of $\Delta(B-R)$ and of the B/T contribution from new bulge growth for model blue-centered galaxies. See § 5.3. Solid lines indicate early-type galaxy models, and dotted lines indicate late-type galaxy models. Thin black lines represent short burst timescales for the new bulge growth (τ = 100 Myr), while thick gray lines represent long burst timescales (τ = 1 Gyr).

Figure 11 shows the time evolution of both $\Delta(B-R)$ and the new-bulge B/T. The peak new-bulge B/T reaches 0.5–0.7 for early types and 0.3–0.5 for late types, representing substantial evolution in observed Hubble type relative to the preexisting B/T ratios of 0.2 and 0.04. Even after 4 Gyr of fading, the new bulge still contributes $B/T \sim 0.1$–0.2 for early types and ~0.04–0.07 for late types, implying fractional bulge growth of ~50%–100%. We conclude that our simplified models support the idea that blue-centered galaxies may experience substantial bulge growth, and more detailed modeling would be valuable.

5.4. *Frequency of Blue-Centered Phases*

Blue-centered galaxies make up ~10% of disk galaxies in the NFGS (Table 1). Our population synthesis models suggest plausible durations for the $\Delta(B-R) > 0$ phase of ~0.5–2 Gyr for burst timescales of 100 Myr–1 Gyr (Fig. 11). In reality the blue-centered phase will be shorter to the extent that the starburst reddens as it develops dust. From these numbers alone, we estimate that in the last 10 Gyr, $\gtrsim$50% of disk galaxies have experienced a blue-centered phase, and it is possible that many disk galaxies have experienced two or more blue-centered phases.

However, we know that $\Delta(B-R)$ correlates with luminosity, and we have suggested that large red preexisting bulges or bars in high-luminosity galaxies may mask blue centers. As expected, in the simplified models of § 5.3, we find that

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[9] In contrast, nearly all blue-centered galaxies in the Close Pairs Survey have larger companions. However, this fact appears inseparable from the selection bias inherent in the survey: given that blue-centered galaxies tend to have low luminosities, they will nearly always be the junior companions in a magnitude-limited survey of galaxy pairs.

blue-centered phases are suppressed whenever the peak new-bulge *B*/*T* ratio during the starburst is specified to be smaller than the preexisting-bulge *B*/*T* ratio. Blue centers may also be lost in the context of blue disks: our late-type blue-centered galaxies have somewhat redder disks than the average late-type galaxy, which must at least partly reflect selection bias. We conclude that many non–blue-centered galaxies may have experienced bulge growth by processes similar to those acting in blue-centered galaxies, and the data are *consistent* with a hierarchical scenario in which most disk galaxies experience repeated in situ bulge growth phases driven by interactions and minor mergers.

6. OPEN QUESTIONS

The foregoing analysis leaves two tantalizing questions unanswered. First, are the young bulges forming in blue-centered galaxies likely to be disky? Second, how do blue-centered galaxies fit into hierarchical galaxy formation scenarios?

6.1. *Do Blue-centered Galaxies Form Disky Bulges?*

Sersic *n* analysis is infeasible with the present data and sample, so we cannot determine whether our blue-centered galaxies are forming exponential bulges. However, we can use the Faber-Jackson relation to search for evidence of disky v/σ ratios, in the spirit of Kormendy (1993). Figure 12*a* shows the Faber-Jackson relation for elliptical galaxies and bulges in the NFGS, measuring bulge luminosities from “any light in excess of an inward extrapolation of a constant scale length exponential disk” (Wyse et al. 1997), where the exponential disk profiles come from the outer disk fits in § 5.1. Only four blue-centered galaxy bulges are shown, as the others either lack velocity dispersion data or have M_B or σ measurement errors comparable to the plot scale (note that the instrumental resolution in most cases is $\sigma \sim 60$ km s^{-1}; Kannappan & Fabricant 2001). These four blue-centered galaxy bulges are all offset toward low σ in the Faber-Jackson relation, consistent with disky kinematics as discussed by Kormendy (1993). However, Figure 12*b* shows that their offsets fall within a broad correlation between color and Faber-Jackson residuals. The slope of this correlation is consistent with stellar population effects (by analogy with the arguments in Kannappan et al. 2002, regarding the correlation between color and residuals from the Tully-Fisher relation). Any kinematic diskiness, if present, is hidden in the noise of the color trend.

Nonetheless, the possibility that externally triggered in situ bulge growth may produce disky bulges merits further scrutiny, for two reasons. First, the three prototype kinematically disky bulges discussed by Kormendy (1993) all show possible evidence of interactions and mergers as well as secular evolution. NGC 4736 has a double nucleus in *HST* UV imaging and may be a merger remnant (Maoz et al. 1995; Shioya et al. 1998); NGC 4826 shows counterrotation consistent with a 10 : 1 merger (stars vs. gas and gas vs. gas, Rix et al. 1995); and NGC 7457 has a companion in the NASA/IPAC Extragalactic Database with $\Delta X \sim 30$ kpc and $\Delta V \sim 100$ km s^{-1}. The role of galaxy encounters in shaping these galaxies is an open question.

Second, unlike the collisionless simulations of Aguerri et al. (2001), the hydrodynamic simulations of Scannapieco & Tissera (2003) show that interactions and even mergers can decrease Sersic *n*. Gas inflow and star formation during the premerger orbital decay phase tends to decrease Sersic *n*, while the merger that follows rarely completely reverses the change.[10] Within a hierarchical simulation volume 5 h^{-1} Mpc on a side, Scannapieco & Tissera find that most bulges show Sersic $n \lesssim 1$ by $z = 0$. Further simulations would be valuable to verify these results for larger samples of simulated galaxies.

6.2. *How Do Blue-centered Galaxies Fit into Hierarchical Galaxy Formation Scenarios?*

Scannapieco & Tissera (2003) present a picture in which interactions and minor mergers drive an evolutionary loop

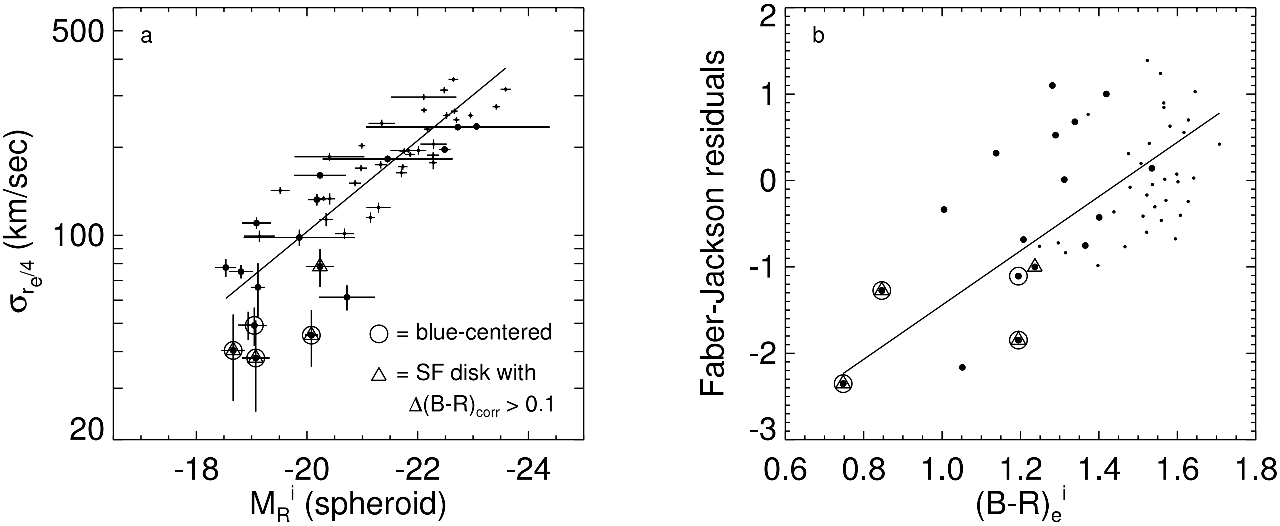

Fig. 12.—(*a*) Faber-Jackson relation for bulges and elliptical galaxies in the NFGS. Large dots represent bulges of star-forming disk galaxies. Small dots represent elliptical galaxies and non–star-forming disk galaxies, which define a tighter relation. Circles indicate blue-centered galaxies, and triangles mark galaxies satisfying $\Delta(B-R)_{\rm corr} > 0.1$ (see § 4). The latter criterion adds the almost–blue-centered galaxy A22551+1931N to the set of galaxies likely to be experiencing active bulge growth. This galaxy has a companion at 11.5 kpc listed in the CfA 2 Survey but below the detection limit of the UZC. The line is a least-squares bisector fit excluding blue-centered galaxies. (*b*) Faber-Jackson residuals vs. $B-R$ colors within r_e. The line is a least-squares bisector fit excluding blue-centered galaxies, with slope 3.1. The slope would be 3.5 without extinction corrections (performed on star-forming disk galaxies only, using the prescriptions of Tully et al. 1998).

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[10] Note that Scannapieco & Tissera use the term “secular” to refer to interaction-driven gas inflow, differing from usage in this paper.

between early- and late-type disk galaxies, somewhat analogous to the loop between elliptical galaxies and disk galaxies seen in lower resolution simulations. As interactions and mergers reshape galaxy bulges, and new thin disks accrete over the thick disks created by previous encounters, at any epoch we observe a snapshot Hubble sequence (see also Steinmetz & Navarro 2002).

This picture offers an alternative to the bulge rejuvenation scenario proposed by Ellis et al. (2001). Using the Hubble Deep Field, Ellis et al. show that bulges are bluer than elliptical galaxies at every epoch to $z \sim 1$, contradicting simplified hierarchical models in which bulges represent old elliptical galaxies around which new disks have grown. The authors find evidence that bulges have been rejuvenated in short bursts of star formation, and they suggest that this rejuvenation may reflect internal secular processes. We suggest instead that both the bursty rejuvenation Ellis et al. observe at high z and the blue-centered phases we observe at low z reflect "high-resolution" hierarchical galaxy formation, involving minor companions and small-scale, local gas physics. In fact, the tabulated data of Ellis et al. indicate a high rate of galaxies with bluer central colors than their overall colors (~30% of the spiral sample described in their Fig. 4), with the caveat that most of the blue excesses do not exceed the errors (R. Abraham 2003, private communication).

The luminosity distribution of blue-centered galaxies at both low and high z may reflect hierarchical processes. At the current epoch, most blue-centered galaxies are fainter than $M_B \sim -20$. This trend may be related to the hierarchical tendency for the faint end of the luminosity function to show continued galaxy formation activity at later epochs than does the bright end (Cowie et al. 1996), and luminosity-dependent color masking (§ 4.1) may be a corollary effect. In this case bright galaxies would have experienced their blue-centered phases at higher redshift, at a time when they enjoyed both a higher merger rate and a greater starburst efficiency, because of larger gas reservoirs. Luminous blue compact galaxies (LBCGs, e.g., Guzman et al. 1996) seen at high z may represent exactly this phenomenon. LBCGs have been interpreted as bulges in formation by Kobulnicky & Zaritsky (1999) and Barton & van Zee (2001), though their exact nature is still an open question.

At low z, analogues of high-z LBCGs often take the form of low-luminosity emission-line S0 galaxies (see the discussion of Barton & van Zee 2001 in Kannappan & Barton 2003). Four of the 11 blue-centered galaxies in the NFGS are emission-line S0 galaxies (including type S0/a, Fig. 2), in keeping with the general abundance of S0 galaxies at low luminosities. Many non–blue-centered low-luminosity S0 galaxies also show central starburst activity and evidence of mergers or interactions (e.g., counterrotating gas and stars; Kannappan & Fabricant 2001 and references therein). We speculate that unlike bright S0 galaxies in high-density environments, low-luminosity S0 galaxies may often represent transient objects caught at one extreme of the morphological evolutionary loop described by Scannapieco & Tissera. If so, then these recently formed bulge+thick disk systems may be destined to fade, regrow thin disks, and finally fill in the low-luminosity spiral sequence.

7. CONCLUSION

Recent research on young and/or "disky" bulges (e.g., Kormendy 1993; Andredakis et al. 1995; Peletier & Balcells 1996; Courteau et al. 1996; Carollo et al. 2001) has pointed to the importance of late-epoch bulge formation within preexisting disks ("in situ" bulge formation). However, this body of work has not resolved an interpretive degeneracy between in situ formation scenarios involving spontaneous disk instabilities and those involving externally triggered instabilities. As a first step toward breaking this degeneracy, we have identified a class of galaxies likely to be experiencing active in situ bulge growth, based on the observation that their centers are bluer than their outer disks (as in Schweizer 1990; Barton Gillespie et al. 2003). To determine whether the primary drivers of the blue-centered phenomenon are external or internal, we have examined the properties and environments of blue-centered galaxies in the Nearby Field Galaxy Survey (NFGS, Jansen et al. 2000a; J00; Kannappan 2001), a statistically representative sample of the low-redshift galaxy population. The NFGS contains eleven blue-centered galaxies (excluding dwarf galaxies and AGNs), all of which are star-forming disk galaxies, with no preferred Hubble type or global environment.

We find that blue-centered galaxies correlate at 95%–99% confidence with two types of evidence of external disturbance: (1) morphological peculiarities, and (2) nearby companions in the Updated Zwicky Catalog (UZC, Falco et al. 1999). The peculiarity correlation is independent of the separate tendency for blue-centered galaxies to have low luminosities (Tully et al. 1996; J00), and in fact the peculiarity correlation strengthens to 99.5% confidence if we correct the color difference parameter $\Delta(B-R)$ (outer disk color minus color within the half-light radius) for the luminosity-$\Delta(B-R)$ trend. However, the UZC companion–$\Delta(B-R)$ correlation may not be independent of the luminosity-$\Delta(B-R)$ trend, because of the fact that lower luminosity galaxies are more likely to have companions in the UZC. On the other hand, many of the apparent companions that seem most likely to be interacting with the blue-centered galaxies in our sample are not listed in the UZC, because these companions are too faint, too close, or already merging. Including this type of evidence, we find signs of possible interactions or mergers for all eleven of the blue-centered galaxies in our study.

We have presented four quantitative plausibility arguments to link these results more directly to the phenomenon of in situ bulge growth. First, the spatial scales of the starbursts in blue-centered galaxies are consistent with the spatial scales expected for bulge growth, especially taking into account the likelihood that bulges and inner disks evolve together (Peletier & Balcells 1996). Second, most blue-centered galaxies in the NFGS appear to be merging or interacting with smaller galaxies, consistent with bulge growth mechanisms that heat but do not destroy disks. Third, schematic population synthesis models tuned to the observed properties of early- and late-type blue-centered galaxies in the NFGS show significant bulge growth, with fractional growth ~50%–100%. And fourth, a duty cycle argument based on the frequency of blue-centered galaxies (~10% of disk galaxies in the NFGS) and a plausible burst timescale (100 Myr–1 Gyr) implies that the majority of disk galaxies have experienced blue-centered phases, possibly more than once during their lifetimes. Although we observe blue-centered phases primarily in galaxies fainter than $M_B = -20$, bright galaxies may well be experiencing almost–blue-centered phases, particularly if the tendency for blue-centered galaxies to be faint simply reflects greater color masking in bright galaxies (i.e., greater dilution of the central blue light by preexisting red bulge populations).

These arguments support the idea that blue-centered phases represent an important mode of in situ bulge growth in the life cycles of most disk galaxies, driven primarily by interactions and mergers with smaller companions. Qualitatively, this scenario fits naturally within the framework of hierarchical galaxy formation, and in fact in situ bulge growth has been observed in high-resolution hierarchical simulations that include small companions and local gas dynamics (Tissera et al. 2002; Steinmetz & Navarro 2002). The hierarchical framework may offer a deeper explanation for the tendency of blue-centered galaxies to be faint: the luminosity trend may reflect the mass dependence of galaxy formation timescales (Cowie et al. 1996). If so, then more massive galaxies should have experienced blue-centered phases at earlier epochs. This prediction agrees qualitatively with evidence for "bulge rejuvenation" in bright galaxies at high *z* (Ellis et al. 2001), and may also be related to the phenomenon of luminous blue compact galaxies (e.g., Guzman et al. 1996; Kobulnicky & Zaritsky 1999; Barton & van Zee 2001). The hierarchical paradigm may even offer a way to make disky bulges: Scannapieco & Tissera (2003) find that premerger gas inflow processes within high-resolution hierarchical simulations help to reshape galaxies toward exponential bulge profiles. Observational studies to date cannot confirm or reject a connection between interactions and disky bulges. In the NFGS, blue-centered galaxies show offsets from the Faber-Jackson relation that are consistent with either disky kinematics or young stellar populations. Evaluating the respective roles of hierarchical and internal secular processes in forming the full variety of bulges in the general galaxy population remains a challenge for future research.

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APPENDIX

NOTES ON INDIVIDUAL OBJECTS

A10504+0454 has no UZC companion, but deep high-resolution imaging (Kannappan, Impey, & Mathis 2004) reveals a possible interacting satellite, undetected in the image shown in Figure 1.

A11332+3536 has noncoplanar counterrotating gas and stars (Kannappan & Fabricant 2001).

A12001+6439 appears smooth at the resolution of Figure 1, but deep high-resolution imaging (Kannappan et al. 2004) reveals loops and filaments suggestive of a late-stage merger.

NGC 3846 has no UZC companion, but its image in Figure 1 shows a trail of debris and two bright knots on the south side suggestive of a merging companion.

NGC 5541 has no UZC companion, but its *K*-band image from the 2MASS All-Sky Data Release reveals that the peculiarity seen at the top of the *B*-band image (Fig. 1) is actually another galaxy, apparently interacting with NGC 5541. High-resolution radio imaging from the VLA FIRST survey (Becker et al. 2003) shows strong emission both in the companion bulge and outside the primary bulge, but not within the primary bulge. The primary bulge is much redder than the bulge of any other blue-centered galaxy and has an Hα equivalent width of only 6.5 Å in emission, despite a very blue region immediately surrounding the red core (Fig. 1) and integrated EW(Hα) $\sim$6.5 Å in emission. Thus, although its $\Delta(B-R)$ identifies NGC 5541 as a rare high-luminosity blue-centered galaxy, its low-luminosity companion probably has more similarities to the rest of our blue-centered galaxy sample than NGC 5541 does.

NGC 5875A has no UZC companion, but its 2MASS color-composite image reveals a large region with distinct *JHK* color on the northeast side of the galaxy, resembling a merging companion.

NGC 7752 appears to be in direct contact with the tidally distorted spiral arm of its larger companion, NGC 7753. The arm is not easily visible at the scale and contrast of Figure 1.

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