THE IMACS CLUSTER BUILDING SURVEY. V. FURTHER EVIDENCE FOR STARBURST RECYCLING FROM QUANTITATIVE GALAXY MORPHOLOGIES*

LOUIS E. ABRAMSON1,2,6, ALAN DRESSLER3, MICHAEL D. GLADDERS1,2, AUGUSTUS OEMLER, JR.2, BIANCA M. POGGIANTI4, ANDREW MONSON3, ERIC PERSSON3, and BENEDETTA VULCANI4,5

1 Department of Astronomy & Astrophysics, University of Chicago, 5640 S Ellis Ave., Chicago, IL 60637, USA; labramson@uchicago.edu
2 Kavli Institute for Cosmological Physics, University of Chicago, 5640 S Ellis Ave., Chicago, IL 60637, USA
3 The Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101, USA
4 INAF-Osservatorio Astronomico di Padova, vicolo dell’Osservatorio 5, I-35122 Padova, Italy
5 Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa 277-8582, Japan

ABSTRACT

Using J- and Ks-band imaging obtained as part of the IMACS Cluster Building Survey (ICBS), we measure Sérsic indices for 2160 field and cluster galaxies at 0.31 < z < 0.54. Using both mass- and magnitude-limited samples, we compare the distributions for spectroscopically determined passive, continuously star-forming, starburst, and post-starburst systems and show that previously established spatial and statistical connections between these types extend to their gross morphologies. Outside of cluster cores, we find close structural ties between starburst and continuously star-forming, as well as post-starburst and passive types, but not between starbursts and post-starbursts. These results independently support two conclusions presented in Paper II of this series: (1) most starbursts are the product of a non-disruptive triggering mechanism that is insensitive to global environment, such as minor mergers; (2) starbursts and post-starbursts generally represent transient phases in the lives of “normal” star-forming and quiescent galaxies, respectively, originating from and returning to these systems in closed “recycling” loops. In this picture, spectroscopically identified post-starbursts constitute a minority of all recently terminated starbursts, largely ruling out the typical starburst as a quenching event in all but the densest environments.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: starburst – galaxies: structure

Online-only material: color figures

1. INTRODUCTION

The quiescent galaxy population has grown since z ~ 1 in all environments (Butcher & Oemler 1978; Faber et al. 2007; Moustakas et al. 2013). Commonly, new passive systems (hereafter PAS) are thought to descend from continuously star-forming galaxies (CSF) in which a “transformational event” depleted or removed cold gas supplies, preventing further star formation (see Renzini 2006, Section 5 and references therein). Starbursts (SBs) are oft-invoked catalysts for this metamorphosis (e.g., Dressler & Gunn 1983; Couch & Sharples 1987; Poggianti et al. 1999; Quintero et al. 2004; Hogg et al. 2006).

Key to the burst-driven evolutionary scenario is the “post-starburst” (PSB; a.k.a. “E+A”/“k+a”) galaxy population (Dressler & Gunn 1983; Zabludoff et al. 1996; Tran et al. 2004). These objects have spectra exhibiting deep Balmer absorption characteristic of short-lived A stars (signifying recent star formation) but negligible emission (signifying little current star formation). Further, they may preferentially occupy a locus in color–magnitude space between the “blue cloud” of star-forming systems and the passive-dominated red sequence (Yan et al. 2009; Mendel et al. 2013). Because these characteristics make PSBs compelling candidates for the CSF–PAS “missing-link,” SBs emerge as important mechanisms enabling the former’s transformation into the latter. But how important are they?

In a previous paper from the IMACS Cluster Building Survey (ICBS; Dressler et al. 2013, hereafter Paper II) we asked: What fraction of passive galaxies descended through the CSF → SB → PSB → PAS evolutionary channel? To address this, we first sought to determine if there were enough intermediate-redshift SBs to account for the growth in the PAS population between then and now.

Surprisingly, we found far too many in all environments less dense than galaxy cluster cores (i.e., the isolated field, field and cluster-infalling groups, and the supercluster environment at Rh > 500 kpc); assuming that the SB and PSB phases have similar lifetimes (200 ≤ τSB ≤ 500 Myr; Poggianti et al. 1999; Oemler et al. 2009) and that all SBs “quench” appropriately, the number of high-mass passive systems should have approximately doubled within a Gyr after z ~ 0.4, far outstripping the observed growth (see, e.g., van der Wel et al. 2007; Moustakas et al. 2013).

Together with our finding of a constant ratio of CSF to SB fractions across all environments, this discrepancy led us to conclude in Paper II that the typical z ~ 0.4 SB does not move into the PSB population after a burst subsides. That is, most SBs do not go on to exhibit a PSB spectrum and then transform into new passive galaxies. Instead, as suggested by Poggianti et al. (1999), we posited that SBs generally return to the “parent” CSF class, remaining in a closed, CSF–SB–CSF recycling loop.

Finding starbursts to be inefficient quenching mechanisms, however, does not mean that they are ineffective in terms of accounting for the increase in the passive fraction with time. To test this, we took the PSBs as proxies for those SBs that are quenching, or at least not participating in CSF–SB–CSF recycling.7

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* Data were obtained using the 6.5 m Magellan Telescopes at Las Campanas Observatory, Chile.
7 We adopt a similar post-starburst definition to that outlined in Poggianti et al. (1999, see their Section 4), ensuring that the majority of these systems are in fact post-burst and not post-truncation galaxies.
Yet still, PAS overproduction—now at earlier times—remained problematic: given the frequency of $z \sim 1$ PSBs (see Lemaux et al. 2010), we expect the passive fraction at $z \sim 0.4$ also to be about twice what we observe.

Combined with a similar constancy of the PAS-to-PSB ratio across all environments, this disagreement suggested that a closed, PAS–PSB–PAS recycling loop must also be active, running parallel to that of the star-forming systems. Hence, many PSBs must descend from passive galaxies, not the other way around.

Combining these findings, we constructed the following hypothesis: star-forming and passive systems, respectively, typically remain in closed-loop cycles, with base levels of star formation or general quiescence punctuated by brief periods of starburst activity. Absent external factors, SBs return to the parent class from which they came with those bursts originating in passive galaxies briefly appearing as prototypical (spectroscopic) PSBs.

Being unable to seriously alter the relative abundances of their parent types, SB/PSBs are thus not transitional stages in CSF → PAS evolution, but transient phases in the lives of these "normal" systems.

Given the constancy of the ratio between parent- and burst-type fractions across a wide range of local densities, we proposed minor mergers involving gas-rich companions as the likely trigger for many intermediate-redshift starbursts (e.g., Mihos & Hernquist 1994; Kaviraj et al. 2009). Additional triggers—such as disk instabilities, tidal encounters, or accretion of cold gas from the intergalactic medium (IGM)—may be operational in the field or in the continuously star-forming population. However, because they occur everywhere (Fakhouri & Ma 2009) and act on all galaxies regardless of host properties (Woods & Geller 2007), minor mergers are the most compelling candidate for a general mechanism.

This scenario works well outside of cluster cores. In these special environments, however ($R_{cl} \lesssim 500$ kpc), the SB-to-PSB ratio approaches unity and the PAS fraction rises substantially, removing the aforementioned PAS overproduction problem. Thus, in agreement with many authors, we suggested that other processes dependent on a dense intracluster medium (ICM)—e.g., ram-pressure stripping (Gunn & Gott 1972) and starvation/strangulation (Larson et al. 1980; Bekki et al. 2002; Moran et al. 2007)—drive traditional CSF → PAS evolution here, by both preventing SBs from returning to a CSF state and actively extinguishing star formation in CSF galaxies. Because gas disks in low-mass companions are not likely to survive the descent into these extreme environments, most PSBs in cluster cores likely do reflect the end-states of CSF-derived SBs instead of mergers onto PAS galaxies.

1.1. An Independent Test

The conclusions described above were based purely on spectroscopy and photometry. However, there is a third avenue by which we can examine the role of SBs in passive galaxy production: galaxy structure. In this paper, we probe the accuracy of our hypotheses from this independent perspective. By analyzing the Sérsic index distributions of the ICBS spectral types as derived from high-resolution near-infrared (NIR) imaging, we will show that the structural relationships between these systems not only support but independently suggest much of the picture we painted in Paper II.

We proceed as follows: Section 2 outlines the ICBS and the data used in this analysis; Section 3 describes our Sérsic index measurement routine; Section 4 presents our results; Section 5 our discussion. We conclude in Section 6. Throughout, we take $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$. All magnitudes are quoted in the 2MASS system unless otherwise indicated.

2. DATA: THE IMACS CLUSTER BUILDING SURVEY

The ICBS is a spectrophotometric survey of four 27'-diameter fields containing five galaxy clusters at $z \sim 0.4$. Its objective is to characterize the evolution of typical galaxies across a range of environmental densities at an epoch in which cluster assembly is vigorously ongoing (Kauffmann 1995; De Lucia et al. 2004; McBride et al. 2009; Gao et al. 2012) and many transformational mechanisms are likely to be active.

Fields were drawn from the Sloan Digital Sky Survey (SDSS; York et al. 2000) and Red-Sequence Cluster Survey (Gladders & Yee 2005) using the cluster-finding technique of Gladders & Yee (2000). Because of its relative insensitivity to relaxation state and our interest in cluster building, we opted for optical selection over gas-dependent techniques (e.g., X-ray selection) to avoid sampling only well-virialized (i.e., built) systems. The latter are, in some sense, the most extreme environments in the universe, so processes occurring there may not reflect those driving the evolution of average galaxies—even those in clusters—at intermediate redshifts.

Details of the optical data comprising the bulk of the survey—obtained using the Inamori Magellan Areal Camera and Spectrograph (IMACS, Dressler et al. 2011) and Low Dispersion Survey Spectrograph III (LDSS3) on the Magellan-Baade and -Clay telescopes, respectively—can be found in Oemler et al. (2013). However, we review key aspects below for convenience.

2.1. Optical Spectroscopy

The ICBS is based on over 4800 spectra ($\Delta \lambda / \lambda \sim 600$) from 42 IMACS and 16 LDSS3 masks (3–4 hr exposures) obtained between 2004 and 2008. The wide field of view of IMACS permits simultaneous coverage out to $R_{cl} \lesssim 5$ co-moving Mpc, allowing relatively unbiased sampling of the entire (super)cluster and projected field ecosystems.

The spectroscopic catalog provides uniform, rest-frame spectral coverage from 3700 to 5200 Å for 2163 objects in the redshift interval $0.31 < z < 0.54$. These systems are roughly evenly split between five "metaclusters" (see below; $N = 993$) and the projected, intervening field ($N = 1170$). Median signal-to-noise ratios (S/N) near 4500 Å range from 30 per 2 Å pixel at $r = 19$ to $\sim 22$ (SDSS system).

In Paper II the data were used to construct new galaxy spectral types and characterize field and cluster group-scale (sub-)structures. Below, we consider the full (super)cluster and its field environments discussed in that paper: (1) the isolated field and (2) the supercluster and cluster-infalling groups ($R_{cl}/R_{500} > 1.5$); (3) the virialized cluster ($R_{cl}/R_{500} \lesssim 1.5$); and (4) the core cluster ($R_{cl} \leq 500$ kpc). We defer a discussion based on local density to a future paper.

In what follows, we also adopt the spectral type assignments from Paper II. However, to ease discussion, we combine starbursts identified by EW(H$\delta$) ("SBH" in Paper II) with those identified by EW([O III] $\lambda3727$) ("SBO") into a single "SB" class, here. The reader should note first that these systems are not necessarily (UL)IRG-like objects, but galaxies whose star formation rates (SFRs) are enhanced by factors of $\sim 3–10$
over the past (few Gyr) average. Again, we are interested in studying processes affecting typical intermediate-redshift galaxies and therefore characterizing the role average (i.e., moderate) starbursts play in galaxy evolution. Stellar-mass ($M_*$) and therefore characterizing the role average (i.e., moderate) starbursts play in galaxy evolution. Stellar-mass ($M_*$) and therefore characterizing the role average (i.e., moderate) starbursts play in galaxy evolution.

### Table 1

| Type                  | Spectroscopic ID | $N_{tot}$ | $N_{tot}$ | $J/K_c$ 5th, 75th Pctle. | $K_c$-band S/N 5th, 75th Pctle. |
|-----------------------|------------------|-----------|-----------|-------------------------|---------------------------------|
| Passive               | PAS              | 457       | 397 (87%)/388 (85%) | 63, 153                 | 68, 130                          |
| Post-starburst        | PSB              | 55        | 44 (80%)/42 (76%)   | 42, 120                 | 50, 119                          |
| Continuously star-forming | CSF            | 1339      | 1077 (80%)/1013 (76%) | 35, 116                 | 50, 115                          |
| Starburst             | SB               | 304       | 213 (70%)/191 (63%) | 30, 92                  | 43, 95                           |

#### Notes.

a Galaxies with $\geq 75$ (50) $J(K_c)$ pixels above $1.5\sigma_{sky}$ with no $r_e$, $b/a$, or $n$ fit flags.

b 233 SBH + 71 SBO.

d 2012 February using the FourStar camera on Magellan-Baade (Persson et al. 2013). At the redshifts considered here, these bands probe the light (dominated by G–K giants) from established stellar populations and are largely insensitive to gas and dust, thus providing almost direct access to the underlying galactic structure that we seek to characterize. These data will be described in detail in a future paper, but we list here properties relevant to the current analysis.

Each IMACS field was tiled with FourStar in a 3 $\times$ 3 mosaic. Final images (~0.25 deg$^2$) were constructed using A. Monson’s pipeline, which employs SExtractor, SCAMP and SWARP (Bertin & Arnouts 1996; Bertin 2010a, 2010b), and IRAF IMCOMBINE to astrometer, zeropoint-normalize, distortion-correct, and co-add all pointings across a mosaic. Astrometric and distortion solutions were computed jointly for $J$- and $K_c$-band images, minimizing filter-dependent systematics that might bias morphological measurements.

Typical limiting depths for these images are $J = 23.3$ and $K_c = 21.4$ (5$\sigma$ point-source, 1$''$ aperture). At magnitudes of $J = 21.0$ and $K_c = 18.5$—encompassing 90%–95% of the spectroscopic targets—these data yield median S/Ns for point sources of 35 (51) in $J (K_c)$.

Table 2 describes the environment and properties of the ICBS sample.

#### Table 2

| Environment            | $N_{tot}$ | $N_{used}$ | $J$ | $K_c$ |
|------------------------|-----------|------------|-----|-------|
| Field + field groups   | 1164      | 1013       | 0.75 | 0.75  |
| Supercluster$^a$       | 471       | 428        | 0.75 | 0.75  |
| Cluster$^b$            | 525       | 435        | 0.75 | 0.75  |
| Cluster core$^c$       | 137       | 114        | 0.75 | 0.75  |
| TOTAL                  | 2160$^d$  | 1634       | 0.75 | 0.75  |
| TOTAL NON-CORE         | 2023      | 1520       | 0.75 | 0.75  |

#### Notes.

a Galaxies within $\pm 3000$ km s$^{-1}$ of $(z)_{cl}$ and $R_d/R_{200} > 1.5$.

b Galaxies within $\pm 3000$ km s$^{-1}$ of $(z)_{cl}$ and $R_d/R_{200} \leq 1.5$.

c Cluster galaxies with $R_d < 500$ kpc.

d Due to guide-star constraints, three objects from the ICBS catalog were not imaged by FourStar.

2.3. NIR Imaging

Structural parameters are derived from $J$- and $K_c$-band images of the four ICBS fields acquired in 2011 November and 2012 February using the FourStar camera on Magellan-Baade (Persson et al. 2013). At the redshifts considered here, these bands probe the light (dominated by G–K giants) from established stellar populations and are largely insensitive to gas and dust, thus providing almost direct access to the underlying galactic structure that we seek to characterize. These data will be described in detail in a future paper, but we list here properties relevant to the current analysis.

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Seizing ranging from 0.5–1.0 in $J$ and 0.3–0.9 in $K_c$ with median values near 0.55 in both bands. Since FourStar pixels are 0.16, the point-spread function (PSF) is well sampled in all but one image, where it is mildly undersampled. As we will show, our results are robust to PSF selection, so no analyses were modified for this field.

3. STRUCTURAL PARAMETER ESTIMATION

Sérsic indexes were measured by fitting single Sérsic profiles using GALFIT v3.0.4 (Peng et al. 2002, 2007), with SExtractor v2.8.6 employed for source detection and ancillary image production. Software has been developed for automated, batch-mode operation of GALFIT—notably GALAPGOS (Barden et al. 2012)—but flexibility is often sacrificed for speed. Because our analysis required a spatially variable PSF and the ability to add model components/parameters was considered useful, we created our own fitting routine.

For each spectroscopic source, a 200 $\times$ 200 kpc stamp was cut from the full, background-subtracted FourStar mosaic and the local gain/exposure time calculated from a coverage map. A local PSF was then either constructed from an inverse-variance weighted stack of the nearest 10 stars or selected from a library of models. The latter were created from multi-component Sérsic fits to candidate PSF stars and visually inspected to ensure quality. Below, we discuss results from five runs using this
implementation (taking the five nearest PSF models) and one run using the composite, empirical PSF. In the interest of clarity, all sample statistics are quoted from the “principal” run using the nearest model PSF.

After PSF selection, SExtractor produced basic positional, geometric, and photometric data for GALFIT input. The source nearest to the spectroscopic catalog location was defined as the ICBS target (“primary”), but all primaries having no pixel within 1′′0 of this fiducial position—derived from histograms of ICBS—SExtractor centroid offsets—were flagged for possible confusion and excluded from later analysis. These tended to occur where the ICBS source was of low to no NIR significance (i.e., rest-frame $B-V \lesssim 0.5$) and resulted in the loss of 57 (136) objects in $J$ ($K_s$).

On-stamp stars were PSF-subtracted before galaxy fitting. Galaxies with $m-m_p < 2.0$ and $|r-r_p| \leq 25$ kpc—where $m_p$, $r_p$ are magnitudes and transverse positions of (primary) sources—were fit jointly with the primary. Pixels outside an ellipse $3.0 \times \text{KRON\_RADIUS}$ from these “fit-worthy” galaxies were masked along with non-fit-worthy sources and star-subtraction cores.

GALFIT was allowed to determine a constant background level for each stamp. Fixing the sky to zero or a value based on non-source pixel statistics does not affect our results, though it can affect fits for individual sources (see Section 4).

“Successful” fits were those whose output parameters (half-light radius, $r_e$; axis ratio, $b/a$; and Sérsic index, $n$) converged away from fitting constraints and were not flagged as unreliable by GALFIT. The first condition essentially imposed a minimum-size criterion, which, through experimentation, was found to be $\sim 75$ pixels ($J$) or $\sim 50$ pixels ($K_s$) detected at $\geq 1.5\sigma$ above sky fluctuations. We apply this (somewhat arbitrary) cut, roughly limiting the sample to $S/N \gtrsim 20$, but note that adjusting it either way has a negligible effect on our results.

After excluding misidentified, poorly fit, and small sources, the final sample contains 1731 (1634) galaxies in $J$ ($K_s$) suitable for analysis. As shown in Table 1, the failure rate is unbiased with respect to spectral type at the $\sim 10\%$ level in $J$ (which we use for the majority of our analyses) so we do not correct for differential failure rate in what follows.

### 4. RESULTS

The model presented in Paper II suggests that SBs and PSBs should physically resemble CSF and PAS galaxies, respectively, but not each other. This is a statement about galaxy morphology and structure. Ideally, we would test our model in terms of the former as fine-grained details (e.g., the presence of spiral arms or tidal features) place the strongest constraints on formation and transformation mechanisms. However, for sources at $z \sim 0.4$ true morphologies can be assessed only from space-based imaging and covering the ICBS with the Hubble Space Telescope (HST) would require hundreds of pointings, which is practically unfeasible.

Fortunately, high-quality ground-based data (such as we have obtained) are more than adequate to characterize the basic structural properties of our systems. Since determining even the average diskiness or bulginess of the spectral types would provide a strong test of our hypotheses, we pursue this avenue here. As is common, we parameterize galactic structure using the Sérsic index, $n$ (Sérsic 1963).

A single, 1200 s HST exposure of the core of one of our clusters (SDSS0845/MACSJ0845.4+0327; Cycle 14 SNAP10491; PI: Ebeling) does exist. We use these data to verify our assessment of the major-merger rate (see Section 5) but do not fit this image because it is in a much bluer bandpass (ACS F606W), contains $\lesssim 4\%$ of our sources (mostly PASs), and, as discussed above, captures a region where we know that our recycling scenario breaks down. Details of the merger comparison are presented in the Appendix.

#### 4.1. Fitting Accuracy

Measuring Sérsic indices to high accuracy is difficult (e.g., Häussler et al. 2007; Hoyos et al. 2011; Yoon et al. 2011). For example, across our six runs, uncertainties in individual fits due to background estimation and PSF selection alone range from $\sim 5\%$ at $n = 1$ to $\sim 30\%$ at $n = 4.0–4.5$, irrespective of spectral type. Yet, because we are interested in the relationships between classes of galaxies—and therefore index distributions—we avoid many of the complexities associated with this endeavor. For our purposes, measured differences will be quantitatively meaningful provided that the fits (though uncertain) are unbiased, i.e., provided that the spectral types span comparable $S/N$ ranges. As this is the case (see Table 1), relative comparisons between distributions are reliable.

That said, we believe that our measurements are reasonably accurate in an absolute sense as well. Though we have not tested our routine on simulated sources, we can assess our fitting accuracy qualitatively and quantitatively in several ways.

Qualitatively, our measured Sérsic indices correlate well with visual impressions. Figure 1 shows $J$-band cut-outs for some of our higher-$S/N$ sources. As $n$ increases, systems clearly progress from disk- to bulge-dominated. Comparisons of ICBS Sérsic index histograms (not shown) also appear consistent with optical results from the low-redshift, Wide-field Nearby Galaxy Cluster Survey (Fasano et al. 2012, see their Figure 18). From these, we find our PASs to be consistent with a mixed S0/E population and our CSFs to be similar to local spirals, as expected.
Figure 2. Left: magenta and cyan dashes are, respectively, the folded, cumulative, \( z \)-band Sérsic index distributions (see Section 4) for \( \sim \)29,300 red and \( \sim \)14,400 blue galaxies from the SDSS. Objects are drawn from the group catalog of Yang et al. (2007) with measurements from the VAGC. Red and blue shaded areas are the \( J \)-band distributions for \( \sim \)400 PAS and \( \sim \)1100 CSF galaxies from the ICBS, respectively. Thickness represents the minimum/maximum values obtained at a given \( n \) over six fitting runs. Right: a comparison of our \( J \) (solid) and \( K_s \) (striped) results (striped areas). Combined with Figure 1, the consistency of these results gives us confidence that our measurements are (at least statistically) sufficiently robust for the present analysis.

(A color version of this figure is available in the online journal.)

Table 3

| Type | \( \mathcal{L}(\ell) \) PAS (dex)\(^9\) | Median (\( n \)) | IQR (\( n \))\(^9\) | \( f(\ell < 2)\)^\(f\) |
|------|-----------------|--------------|-------------|-----------------|
| PAS  | \( J \) \= 3.1 \pm 0.1, \( K_s \) \= 3.7 \pm 0.3 | \( J \) \= 2.9 \pm 0.2, \( K_s \) \= 3.1 \pm 0.4 | \( J \) \= 0.23 \pm 0.02, \( K_s \) \= 0.15 \pm 0.02 |
| PSB  | 4.1 \pm 0.6, \( J \) \= 2.9 \pm 0.5, \( K_s \) \= 3.2 \pm 0.2, \( J \) \= 3.4 \pm 0.3, \( K_s \) \= 3.2 \pm 0.3 | 0.26 \pm 0.03, \( K_s \) \= 0.27 \pm 0.01 |
| CSF  | 1.5 \pm 0.1, \( J \) \= 1.7 \pm 0.1, \( K_s \) \= 1.9 \pm 0.1, \( J \) \= 2.2 \pm 0.1 | 0.62 \pm 0.01, \( K_s \) \= 0.56 \pm 0.01 |
| SB   | \( J \) \= 25 \pm 1, \( K_s \) \= 26 \pm 1 | \( J \) \= 1.3 \pm 0.1, \( K_s \) \= 1.6 \pm 0.1 | \( J \) \= 1.4 \pm 0.1, \( K_s \) \= 1.7 \pm 0.1 | \( J \) \= 0.70 \pm 0.01, \( K_s \) \= 0.64 \pm 0.01 |

Notes.

\(^9\) Logarithmic likelihood that a distribution is drawn from the PAS over the CSF parent. Positive values denote that the sample is more likely to have come from the PAS class.

\(^f\) Inter-quartile range; 75th minus 25th percentile.

\(^f\) Fraction of galaxies with \( n < 2 \).

Quantitative assessments are provided in Figure 2. In the left panel, we compare \( z \)-band fits from the NYU Value-Added Galaxy Catalog (VAGC; Blanton et al. 2005) for photometrically selected red and blue SDSS galaxies to \( J \) measurements (roughly rest-frame \( z \)) of our PAS and CSF systems. To approximate the mean ICBS environment, the comparison sources (\( z \leq 0.1 \)) were drawn from the group catalog of Yang et al. (2007).

In this and all similar plots below, we show folded cumulative distributions, i.e., cumulative distributions reflected at their medians. This (somewhat non-traditional) format gives a good sense of a distribution’s width and skew—as a histogram would—while avoiding binning. A complication is that ordinates are reversed at every median. Hence, the reader must use the left-hand axis to interpret the rising part of each band, but the right-hand axis to interpret the falling part.

There is a systematic shift of \( \Delta n \approx -0.5 \) and slightly longer high-\( n \) tails in the ICBS distributions, but the global similarity of these to the SDSS/VAGC results is apparent. Given the possible influence of redshift evolution, color versus spectroscopic selection, differences in fitting methods, source resolutions,\(^9\) and sample size—in addition to any real fitting errors—the correspondence between these results suggests that our measurements are robust for our purposes. Ultimately, the most relevant aspect to note is the near-identical separation between red and blue distributions in either sample, implying that both analyses have comparable power to discriminate between disks and spheroids.

We plot the results of a final test in the right-hand panel of Figure 2, showing an internal cross-check of our \( J \)- and \( K_s \)-band results. Encouragingly, agreement is good. The small systematic offset between the two measurements could again be due to many factors besides fitting error. Some of the shift may be physically meaningful (a factor of two in wavelength separates the bandpasses), but the loss of low-surface-brightness features (e.g., disks) due to the higher sky backgrounds in \( K_s \) surely also plays a role. Regardless, because the offset is essentially uniform, errors contributing to it should not introduce a bias, allowing meaningful comparisons of results obtained independently in either band. Indeed, as shown in Table 3, our main results hold across both.

This being the case, given the higher fitting success rate in \( J \) band, we focus on these results below.

4.2. Spectral-type Distributions

The left panel of Figure 3 presents our first main result: the full Sérsic index distributions for all reliably fit ICBS galaxies. Distribution widths correspond to the minimum/maximum values obtained at a given \( n \) over the six fitting runs discussed in Section 3. We introduce our analytical processes and comparison metrics here before testing the effects global environment and mass completeness have on this result.

The two most obvious characteristics of this plot are also the most important. First, the SB−CSF and PSB−PAS distributions, respectively, display unambiguous similarities. Second, there

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\(^9\) FWHM\(_{SDSS} \approx 1\prime.2 = 1.4 \) kpc at \( z = 0.06 \), while FWHM\(_{ICBS} \approx 0\prime.5 = 2.7 \) kpc at \( z = 0.40 \). Alternately, at those redshifts, 1 kpc spans 2.2 SDSS pixels, but only 1.2 FourStar pixels. Both types of “resolution” affect the accuracy of GALFIT.
is an equally clear disparity between the SB and PSB distributions; the former is shifted to values characteristic of disks ($n \sim 1$), while the latter is shifted to those of bulge-dominated systems ($n \sim 3$–4). Although the dissimilarity of the PAS and CSF distributions links these conclusions, there is no a priori astrophysical reason to expect SBs to resemble their supposed antecedents (CSFs) but not descendants (PSBs). Later, we will argue in Section 5 that this is the only physically acceptable interpretation for most of these systems.

4.3. Mass Incompleteness

So far we have examined the full magnitude-limited ICBS sample ($r \lesssim 22.5$). Because it gives maximal statistical leverage, this is the best sample to use to characterize the spectral types individually. However, since the types span slightly different mass ranges (see Paper II, Figure 2) it might bias comparisons between them. To determine if this is the case, we reanalyze a sub-sample containing only galaxies with $M_* > 2.5 \times 10^{10} M_\odot$ (Salpeter initial mass function; see Oemler et al. 2013) corresponding to the $\sim 80\%$ ICBS completeness limit. The results are plotted in the right-hand panel of Figure 3.

Clearly, the global trends from the full sample remain largely unchanged; using our log-likelihood statistic, we find $\mathcal{L}(\text{PSB} \in \text{PAS}) = 1.6 \pm 0.7$ for the PSBs with $P_{\text{K-S}}(\text{PSB} \in \text{PAS}) > 0.4$ for five of the six runs, but $P_{\text{K-S}}(\text{SB} \in \text{PAS}) < 13$. (Note that some of the change in likelihoods is driven by the reduction in sample size.) Although the mass-limited CSFs appear slightly bulgier—perhaps reflecting the correlation of bulginess with mass (Benson et al. 2007; van der Wel 2008; Bell et al. 2012)—the SBs are still clearly structurally related to these systems and equally clearly distinct from the PSBs.

Since mass incompleteness does not seem to significantly affect our results, we will continue to use the magnitude-limited sample below.

4.4. Environmental Dependence

All results above were derived using a combination of cluster (core + non-core), supercluster, and field galaxies. Findings from Paper II suggest that such mixing is permissible: the fractional relationships between the spectral types point to recycling being active (if not dominant) everywhere outside of cluster cores. However, we now test this assumption using the structural data. We begin by plotting separately the Sérsic index distributions for the field, supercluster, and cluster samples in Figure 4.

In the field (top) the picture is identical to the combined result; we find $\mathcal{L}(\text{PSB} \in \text{PAS}) = 3.3 \pm 0.6$ for PSBs, but $\mathcal{L}(\text{SB} \in \text{PAS}) < -12$ for SBs. In fact, if anything, the picture here is even clearer: PSBs and SBs have $\langle P_{\text{K-S}} \rangle \sim 0.5$ of...
yielding S´ersic distributions for three of the ICBS large-scale environments.

Figure 4. S´ersic distributions for three of the ICBS large-scale environments. From top: field (isolated galaxies and groups); supercluster (infalling galaxies and groups); virialized cluster and cluster core. In the field, the burst classes are statistically indistinguishable from their respective non-burst “parents.” In the supercluster, though we have little power to constrain the post-starbursts, the active bursts retain strong similarities to the CSF types. In the cluster, both burst types diverge from the non-bursts; PSBs here are diskier than their field counterparts, resembling the CSFs as closely as they do the PASs. These shifts suggest that additional mechanisms may be at work in these dense environments. (A color version of this figure is available in the online journal.)

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belonging to the PAS or CSF parent, respectively, with no run yielding \( P_{K,S} \) < 0.2.

In the supercluster (middle), though likelihoods drop significantly (due in part to the smaller number of systems), the same general trends emerge for the SBs as seen in the field. These systems exhibit \( \mathcal{L}(SB \in PAS) < -6 \), their distribution reflecting the shape of the CSFs to high fidelity though the latter move to slightly higher \( n \) overall. The lack of PSB systems prohibits us from constraining their relationship to the PASs, but we note that the two well-fit PSBs in this environment have S´ersic indices falling precisely at the median value of the PAS distribution \( n \approx 3 \).

However, in the cluster proper (bottom) the picture changes. First, it is clear that CSFs in this environment are considerably more bulge-dominated than those in the field. Their subtle departure from the SBs in the supercluster is also exacerbated. This displacement may simply be a manifestation of the well-known morphology–density relation (Dressler 1980; Dressler et al. 1997; Postman et al. 2005), though interestingly it is not seen in the PAS population. Conversely, cluster PSBs appear to be diskier than their field counterparts, moving closer to the star-forming systems. This shift is reflected by the K-S statistics: with \( 0.1 < \mathcal{L}(PSB \in PAS) < 1 \), PSBs appear only marginally more likely to have come from the PASs over the CSFs.

Yet, PAS–PSB–PAS recycling may still be active in the cluster environment. If the dense ICM of the cluster core is providing additional processing as we expect, core galaxies may be significantly biasing otherwise similar trends away from those of the field and supercluster.

We test this in Figure 5, plotting the distributions for a “core-only” sample (left) and the cluster with those galaxies removed (right). Although statistics are limited, much of the shift to diskier PSBs indeed appears to be driven by systems in the innermost 500 kpc of the cluster (modulo projection effects) where ram-pressure or tidal stripping may be playing large roles.

Comparing the core-excised sample to the full cluster sample (Figure 4, bottom) reveals the gap at low-\( n \) between the PSBs and PASs to have largely disappeared. Though, to the eye, there may still be some ambiguity between the non-core PSBs and CSFs at low \( n \), the K-S metric reveals the former now to be 63 times more likely to have come from the PASs on average, up from \( \sim 3 \) in the full cluster sample. The raw K-S probability \( P_{K,S}(PSB \in PAS) \) is also always greater than 0.2, while in four of the six runs \( P_{K,S}(PSB \in CSF) \) is less than 1%.

We note that these likelihoods represent conservative bounds to the true probabilities since the core-excised sample almost certainly includes “overshoot”/“backsplash” galaxies (Balogh et al. 2000; Moore et al. 2004; Bahe et al. 2013), i.e., systems that have been processed by the core but now lie at larger radii.

Given the trend of K-S results, it seems that the unprocessed cluster population likely exhibits the same structural connections as those in the field and supercluster environments. An examination of galaxies in field and cluster-infalling groups also yields results entirely consistent with those of the field and supercluster. Thus—as suggested in Paper II—it indeed seems that there are only two significant environments in terms of the relationships between the spectral types: the highest-density regions of the universe, and everywhere else.

If galaxies living “everywhere else” (i.e., the overwhelming majority of systems) are examined, one obtains the distributions plotted in Figure 6. Here, the spectral type relationships are entirely unambiguous. Statistics—medians, inter-quartile ranges, \( n < 2 \) fractions, and \( \mathcal{L}(child \in PAS) \) values—describing these “non-core” distributions are presented in Table 3. Unless otherwise specified, the discussion in the next section will refer to this sample.

5. DISCUSSION

As shown in the previous section, the structural connections between the spectral types are the same as those exhibited by their population fractions: the SB and CSF as well as PSB and PAS types resemble each other closely, but the active- and post-starbursts are highly dissimilar. However, while necessary, showing that SBs are disk-dominated and PSBs are bulge-dominated is not sufficient to demonstrate that the closed recycling loops we posited are in fact operational. Indeed, many others—using both one-dimensional and two-dimensional fitting techniques—have found low-redshift PSBs to be comparably bulge-dominated to passive systems (see, e.g., Quintero et al. 2004; Balogh et al. 2005; Yang et al. 2008;
Mendel et al. 2013; Belle et al. 2012) but used this to support the

Figure 5. Left: J-band Sérsic index distributions (Rcl ≤ 500 kpc). While the active starbursts in cluster cores are still disky, the parent–daughter relationships between the burst and non-burst classes in this environment are substantially degraded. Notably, the post-starbursts in the core have Sérsic indices between those of the SBs and PASs (or, alternately, close to those of the CSFs). These facts suggest that mechanisms unique to dense environments (e.g., ram-pressure stripping or starvation) may be causing a “leak” from CSF to PAS populations through active quenching or starburst-driven evolution. Population fractions from Paper II also suggest that the latter is occurring, here. Note that, when this population of objects is removed (right panel), the relationship of cluster PSBs to the PASs is strengthened compared to the full cluster sample shown in the bottom panel of Figure 4.

(A color version of this figure is available in the online journal.)

Figure 6. Final Sérsic distributions for all galaxies residing outside of cluster cores. Properties are listed in Table 3.

(A color version of this figure is available in the online journal.)

most PSBs do not descend from CSF-derived SBs. To test the second statement, we again take the PSBs as proxies for all SBs not involved in CSF–SB–CSF recycling. The bulginess of these systems then suggests one of two things: (1) PSBs represent the subset of CSF-derived SBs that have undergone major transformational events (i.e., major-mergers) and are now quenching; (2) PSBs originate in systems that are bulge dominated ab initio.

Unfortunately, the structural similarity between the PSB–PAS classes alone is not enough to clarify this ambiguity. As they are bulge dominated, pressure support is significant in the non-star-forming systems. Therefore, we would not expect the signature of any transformational mechanism to be easily detectable. Hence, given only a strong “family resemblance,” we cannot immediately differentiate between the two cases outlined above. However, we can make progress by attacking the problem from the opposite end, asking: Are there sufficient SBs involved in major mergers to account for the PSB population? If so, PSB → PAS evolution could explain the structural trends. If not, our recycling scenario would be favored.

To address this question, L.A. performed a visual inspection of the J-band data, looking for galaxies that displayed clear signs of interactions with similar-sized neighbors without reference to their spectral type.11

Each object was graded from 0 to 2 (0 = no evidence of merging, 2 = definite merger in progress) with a subset graded twice after a random rotation and/or reflection. Of these objects, about 10% moved from grade 1 (possible merger; close/small companion or tidal feature) to 2 (obvious disruption from neighbor, large tidal tails, “train-wreck” appearance) upon second viewing. This “upgrade” rate agrees well with that obtained by comparing ground- to space-based grades using the single HST ACS image in the ICBS footprint (see Section 4 and Appendix). Hence, we include as “confirmed” major mergers all grade 2 plus an additional 10% of the number of grade 1 systems. Representative cut-outs are presented in Figure 7.

We did not quantify mass ratios for these possible mergers. However, the comparable sizes and luminosities of the galaxies

11 Results from HST data are inconclusive. Cluster surveys (e.g., Dressler et al. 1999; Tran et al. 2003; Poggianti et al. 2009) find PSBs to be generally pristine late- or early-type disks. Field studies (e.g., Tran et al. 2004; Yang et al. 2008) find many to display morphological irregularities indicative of recent mergers.
involved suggest that the usual 1:3–1:1 definition for “major” mergers applies (see Figure 7).

In our combined, mass-limited, non-core sample (drawn from the full ICBS catalog, not the subset of successfully fit galaxies) L.A. found $3_{-1.0}^{+3.0}$% (PAS) to $6_{-1.5}^{+2.0}$% (SB) to be involved in major mergers. Errors reflect 68% confidence assuming a “beta distribution” for merger probabilities (Cameron 2011). This result agrees well with that of Bell et al. (2006), who find $5\pm 1$% of all galaxies at $0.4 < z < 0.8$ to be merging using the same stellar-mass limit we apply ($M_* \geq 2.5 \times 10^{10} M_\odot$), and also Williams et al. (2011), who find a 6% ± 1% merger fraction for galaxies at $0.4 < z < 2.0$ with $M_* \geq 3.2 \times 10^{10} M_\odot$.

Indeed, an independent inspection by A.O. yielded merger fractions 40% lower than those quoted above, in agreement with a previous HST study of $z \sim 0.4$ groups by Wilman et al. (2009), see their Table 1). While they may therefore be closer to upper bounds, since we wish to constrain the maximal impact of major mergers, we discuss the more generous estimates in what follows.

For the SB class, this fraction corresponds to 11 systems. There are 26 PSBs in the sample. At face value then, the number of major-merging active SBs can account for perhaps a third to half—but not most—of the PSBs. Notably, this is very similar to the offset between our PSB fraction ($\sim 2\%$) and that estimated to be due to major mergers at $z \sim 0.4$ from Snyder et al. (2011). Starburst recycling must therefore be a very active (if not dominant) as we suggest in Paper II.

Although, as discussed above, we believe it is fairly accurate, we acknowledge that this is an imprecise estimate. Two systematics drive this uncertainty: merger identification and remnant properties. We constrain the effects of these issues, showing that they should not invalidate the scenario we have outlined above, in the following sections.

### 5.1. Merger Identification Uncertainties

Regarding the issue of identification, there are two concerns: (1) merger features (e.g., tidal tails) may not be obvious at all merger stages; (2) mergers might occur on timescales much shorter than those over which spectral indicators change. If either is the case, we would underestimate the true number of merging SBs.

With respect to the latter concern, while the range of theoretical values for major-merger visibility timescales is large—radial separations and morphological disturbances depend on the myriad configurations and properties of the galaxies involved—it seems safe to say that $\sim 0.5–2$ Gyr are reliable bounds (e.g., Lotz et al. 2008; Conselice 2009; Lotz et al. 2010a, 2010b). Considering that our data span approximately 2 Gyr and SB indicators are sensitive to timescales $\geq 200$ Myr, neither our data set nor spectral categorization should significantly undersample the merger rate. That is, our data provide a sufficiently long baseline to capture most of a merger and our spectral definitions respond quickly enough to ensure that most merging SBs fall in the SB class.

Misidentification of merging systems as non-mergers—because, for example, the galaxies are at large separations, have just coalesced, or do not display disturbed morphologies—is more problematic. Turning to Lotz et al. (2008, see their Figures 4 and 11) and examining their “Sbc” model (slightly more massive than our average SB but consistent with its diskiness), we find that, although (projected) pair separations of $> 50$ kpc are expected to last for perhaps $20\%$ of a merger, high SFRs can persist after coalescence for almost a gigayear. Thus, missing mergers due to partners falling off inspection stamps should not be a significant problem, but grading “just-merged” systems as non-mergers might be.

Fortunately, asymmetry metrics can be high during this period. Although a comparison of visual to quantitative metrics is not ideal, this suggests we should have captured many coalesced objects; highly disturbed “isolated” systems would receive high merger grades.

Hence, we believe that the dominant source of identification uncertainty is likely to be the fraction of a merger over which prominent asymmetries are visible, which is about a third to half. In the maximal case, then, we might have underestimated the number of major-merging SBs by a factor of about three.

However, though identification uncertainties might in this way permit the SB merger fraction to account for the number of PSBs, uncertainties in the efficacy of such events in creating bulge-dominated, quiescent remnants appear to run in the opposite direction.

### 5.2. Uncertainties in Remnant Properties

Interestingly, none of the “Sbc” mergers from Lotz et al. (2008) terminate in non-star-forming systems. Although these authors do not employ feedback from active galactic nuclei in their simulations, the effectiveness of this process in stifling star formation or leading to PSB remnants remains questionable (Brown et al. 2009; Wild et al. 2009; Debuhr et al. 2010, 2011; Snyder et al. 2011). Further, according to Hopkins et al. (2010, see their Figure 15), assuming most of our disky SBs are indeed CSF-derived or fall into their “gas-rich” category, bulge formation is preferentially suppressed in mergers of these systems compared to those involving bulge-dominated or gas-poor galaxies. Combined, these effects might substantially reduce the number of major-merging SBs that could result in both bulge-dominated and quiescent remnants, i.e., systems that actually resemble our PSBs.

One could argue that the companion of a merging SB—which may not be captured in the spectroscopic catalog—might be bulge dominated or gas-poor and thus that the remnant would
efficiently grow a bulge. However, mergers involving local red and blue galaxies—a proxy for this scenario—have been estimated by Chou et al. (2012) to be about 10 times more common than mergers involving two blue galaxies. Therefore, though the analogy is not perfect, the probability that most of our SB mergers have a gas-poor companion appears low.

There may also be a more general constraint to consider. Both numerical (e.g., Lotz et al. 2008, 2010b) and observational studies (e.g., Poggianti et al. 1999) suggest that bulge building (in mergers or otherwise) is delayed with respect to the cessation of SB activity. If the delay is significant and a large portion of PSBs come from CSF-derived SBs (likely to be disk dominated), then a substantial fraction of PSBs should be disky. This is clearly not the case (see Table 3).

In sum, uncertainties in remnant properties and the effects of delayed morphological versus spectroscopic transformation probably (greatly) suppress any boosts misidentification issues give to the number of major-merging SBs. So, although we cannot rule out CSF-derived, major-merging SBs as progenitors of a sizable fraction of our PSBs, it seems unlikely that they are responsible for most of this population given the factor of ∼2–3 baseline short-fall in numbers.

5.3. Environments of Major Mergers: An Additional Constraint

One final piece of evidence speaks against a CSF-derived, major-merger-driven origin for most PSBs: the cluster galaxy correlation function. As shown in Paper II (see Figures 4 and 6, therein) the active- and post-starburst (at least in clusters) have very different spatial distributions. Perhaps unsurprisingly, the SBs track the CSFs, appearing relatively uniformly over the faces of our clusters, while the PSBs track the PASs, remaining centrally concentrated. (Recall the paucity of PSBs in the supercluster sample, above.) Therefore, even if we have somehow massively underestimated the number of mergers or if all of the merging SBs will in fact become quiescent spheroids (neither of which we think is true), they would still have to rearrange themselves spatially in order to account for all of the PSBs.

To test this, we relaxed our definition of “confirmed” major mergers to include all (mass-complete) SBs with grades >0 and compared the local environments of these galaxies to those of the PSBs. (There are too few of these systems to adequately constrain their correlation function.) The results—using the surface density of a galaxy’s 10 nearest neighbors to parameterize “local environment”—are plotted in Figure 8.13

From these histograms we see that (plausibly) merging SBs live in regions with densities similar to those of the rest of the SB population. The PSBs, however, clearly do not. Indeed, approximately half of the latter are found at densities where there are no major-merging SBs (though still some non-merging SBs).

A larger sample is needed to draw definitive conclusions, but these data suggest that many major-merging, CSF-derived SBs do not have the proper spatial distribution to be the progenitors of our PSBs, even if the aforementioned uncertainties in merger fractions, etc., might allow them to account for the total number of these systems. Further, tests show this result to be independent of SFR, $M_*$, and $n$. Hence, if anything, this plot suggests that we may have overestimated the impact of mergers by about a factor of two; only half of our PSBs live in similar environments to those of the merging SBs. This further reduces the impact of possible misidentifications discussed above.

These results might appear to disagree with those of Kocevski et al. (2011), who, in a study of $z \sim 0.9$ clusters, found a larger fraction of SBs (∼25%) to be merging and to prefer high-density environments. However, this analysis focused mainly on LIRGs, objects with substantially higher 24 μm fluxes and SFRs than our typical SB (see Section 2.1 and Paper II). Combined with possible evolution in the SB population between $z \sim 0.9$ and $z \sim 0.4$ ($\Delta t \approx 3$ Gyr), the fact that our sample contains very few LIRGs may explain why we do not see a similarly enhanced major-merger rate or preference for high-density environments in our SBs.

It is of course possible that a conspiracy is at work, i.e., that PSBs reflect the most efficient bulge-forming mergers and we are missing those SBs that recently underwent a major merger in the denser regions of our superclusters.

However, a more straightforward interpretation of the data—which show a close resemblance of the PSBs to an existing population of appropriately bulge-dominated galaxies with an inherently similar spatial correlation function—is that a large fraction of these galaxies are simply born from the passive population. If so, a non-star-forming PAS–PSB–PAS recycling loop is almost certainly operating in parallel to the star-forming loop described above.

We stress that, from a purely spectroscopic standpoint, this result is surprising. Figure 9 shows composite spectra of the ICBS spectral types. The resemblance between our SBs and PSBs (especially in the depth of Hα, higher-order Balmer lines, and the relative strengths of Ca H and K) is apparent, the latter appearing essentially as emission-less versions of the former. Hence, given only these data, the evolutionary scenario has great appeal! It is only when information is combined across multiple domains—photometric, spectroscopic, and morphological—that persuasive alternative interpretations emerge.

5.4. The Starburst Mechanism

A range of plausible (if not operational) triggering mechanisms are consistent with the SB–CSF structural relationship we find. These include tidal disruptions, intrinsic disk

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13 This analysis for field galaxies reveals no significant difference between the density distributions of any of our spectral types. This is likely because the spectroscopic catalog samples the volume in this environment too sparsely to obtain a meaningful measurement.
instabilities, and gas accretion, as well as minor mergers. However, minor mergers appear to be the most likely candidate for producing the PAS-derived SBs that lead to most PSBs. The reason is simply that passive galaxies lack large gaseous disks and are known to possess hot halos that would stifle cold-mode IGM accretion (Forman et al. 1985; Mulchaey & Jeltema 2010). Further, taking numbers from Lotz et al. (2011) and Newman et al. (2012), respectively, minor-merger rates of ~3 times the major-merger rate and close-companion fractions of ~13%–18% are both about the right size to allow these interactions to explain the ~1:10 PSB:PASS ratio we find. While we cannot definitively say what fraction of all SBs (CSF- and PAS-derived) are the result of minor mergers, it is reasonable to suspect that these events occur in a similar fashion across PAS/CSF hosts (Woods & Geller 2007), suggesting that such interactions could be a significant contribution to active galaxies in general.

5.5. Cluster Cores: An Aside

As noted in Section 1, the recycling scenario discussed above is expected to break down in cluster cores. Here, the SB:PSB ratio climbs to ~1 and the PAS fraction rises rapidly at the expense of the CSFs, implying that CSF → PAS evolution is active. This is not surprising: the dense ICM in these regions should prevent infalling SBs from rejoining the CSF population (breaking the star-forming recycling loop) and—as has been known for decades—actively quench CSF galaxies through, e.g., ram-pressure stripping. While SBs are thus only incidentally connected to PAS build-up—the global extinguishing of star formation affects the more numerous CSFs as well as the SBs—we do expect them to be the dominant source of core PSBs: no low-mass, gas-rich systems should survive long enough in these regions to accrete onto PASs.

Though projection effects and small sample size prohibit drawing definitive conclusions, the plot of cluster core Sérsic index distributions in Figure 5 (left) suggests that something consistent with this scenario is taking place. Here, the PSBs are seen to lose their high-$n$ tail (as noted previously by the MORPHS collaboration; Dressler et al. 1999) and depart significantly from the PASs, falling squarely between these and the still-disky SBs. This is the signal we would expect if core SBs and PSBs reflect larger-radius accretions onto disky CSFs and their subsequent ICM-driven quenching. However, the similarity of core PSBs to core CSFs also suggests that some of these systems may reflect ICM-triggered bursts (Bekki & Couch 2003) or the most extreme examples of post-truncation galaxies.

6. CONCLUSION

Using large, mass- and flux-limited samples from the IMACS Cluster Building Survey, we measured the Sérsic indices for intermediate-redshift galaxies of all spectral types from high-quality ground-based NIR imaging. Our results support the existence of a starburst recycling scenario presented in Dressler et al. (2013) operating in environments from the isolated field to rich clusters. We find:

1. little to no structural similarity between active- and post-starburst systems outside of cluster cores, indicating that CSF → SB → PSB → PAS evolution is weak in almost every environment modulo some uncertainty about the contribution of major mergers;
2. strong structural ties between SB–CSF and PSB–PAS classes, suggesting that most PSBs are transient “blips” in the lives of ordinary star-forming and quiescent galaxies and do not represent stages in galaxy “quenching”;  
3. the star-forming/-bursting systems to be disky, everywhere. Taken with the above relationships, this independently suggests that a gentle mechanism (likely minor mergers) is responsible for the production of the typical intermediate-redshift starburst;
4. evidence that this picture may reverse in cluster cores, with environmentally specific agents providing a channel for CSF → SB → PSB → PAS evolution.

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APPENDIX

GROUND- VERSUS SPACE-BASED MERGER GRADES

As mentioned, there exists a single 1200 s HST exposure covering the inner $R_d \lesssim 500$ kpc of one of our clusters in ACS F606W. We inspected the 80 ICBS targets (67, mass-complete sample) on this image for signs of major mergers in a manner identical to that presented in Section 5 above. Reassuringly, although these data are of much higher spatial resolution, we find a merger rate of 6% ± 3% (Poisson error), fully consistent with our ground-based estimate. Even in a system-by-system comparison, Figure 10 (left) reveals that there is little to no bias in merger grades derived from these versus the ground-based data. The scatter in this diagram is also revealing: HST “upgrades” (points above the 1-to-1 dashed line) arise from the enhanced ability to resolve
tidal features in the space-based data. However, an almost equal number of systems become downgraded (pushed below the 1-to-1 line) since blending in the ground-based imaging is also resolved out. Hence, apparently interacting galaxies in the ground-based data become clearly separated in the space-based imaging.

Due to this “slosh,” the integrated probability that a system would be upgraded using space-based data is only +9% (right panel), the same upgrade rate obtained from the ground-based inspection! This good agreement gives us confidence that our merger estimate is, as argued, not biased low, further supporting our conclusion that major mergers are not likely to be a large leak in our SB recycling scenario.

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Figure 10. Merger grades derived from HST ACS vs. Magellan FourStar imaging. Left: system-by-system correlation for galaxies in the mass-complete ICBS sample. Points have been offset for clarity, and half-grades come from averages over repeat assessments. Scatter in this diagram is substantial, but no bias is apparent. Thus, the ground-based merger fractions discussed in Section 5 are, as argued, likely not to be underestimated. Systems “upgraded” in the HST data tend to have tidal/small-scale features unresolved from the ground, but this enhanced resolution also separates blended galaxies, reducing their ground-based grades. Right: histogram of grading offsets. Positive offsets indicate “upgrades” using HST data. Overall, these offsets amount to less than a 10% increase in the probability that a galaxy would have received a higher merger grade if space-based data were available for all sources. This is consistent with the upgrade rate derived from repeat inspections using the ground-based data and thus already accounted for in the estimates discussed in the text. (A color version of this figure is available in the online journal.)