AN IMAGING AND SPECTROSCOPIC SURVEY OF GALAXIES WITHIN PROMINENT NEARBY VOIDS.
II. MORPHOLOGIES, STAR FORMATION, AND FAINT COMPANIONS

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ABSTRACT

We analyze the optical properties of ~300 galaxies within and around three prominent voids of the Center for Astrophysics Redshift Survey. We determine CCD morphologies and Hz equivalent widths from our imaging and spectroscopic survey. We also describe a redshift survey of 250 neighboring galaxies in the imaging survey fields. We assess the morphology-density relation, EW(Hz)-density relation, and the effects of nearby companions for galaxies in low-density environments selected with a smoothed large-scale (5 h⁻¹ Mpc) galaxy number density n. Both the morphological mix and the Hz line width distribution of galaxies at modest underdensities, 0.5 < n/ n0 < 1, are indistinguishable from our control sample at modest overdensities, 1 < n/ n0 < 2. Both density regions contain a similar fraction of galaxies with early-type (E and SO) morphologies and with absorption-line spectra (∼35%). At the lowest densities, n/ n0 ≤ 0.5, there is a 3 σ shift in the distribution of EW(Hz) away from absorption-line systems (only ∼15%) and toward emission-line systems with active star formation—EW(Hz) ∼ 40–100 Å. There is a 2 σ shift in the morphological distribution away from early types and toward irregular and peculiar morphologies.

The redshift survey of projected companions, 80% complete to m_R = 16.13, demonstrates that the incidence of a close companion in redshift space is insensitive to global density over the range we investigate (0.16 < n/ n0 ≤ 2). However, the typical velocity separation of close pairs drops significantly (>3 σ) from Δcz ≥ 200 km s⁻¹ at 0.5 < n/ n0 ≤ 2 down to Δcz = 103 ± 20 km s⁻¹ at n ≤ 0.5 n0. In the lowest density environments, galaxies with companions clearly (∼4 σ) have stronger star formation than comparable galaxies at larger global density (0.5 < n/ n0 ≤ 2). On the other hand, the distribution of EW(Hz) for galaxies without nearby companions (closer than ∼150 h⁻¹ kpc and 1000 km s⁻¹) varies little over the entire density range. These results, combined with the luminosity- and color-density relations of this sample (Paper I), suggest that the formation and evolution of field galaxies are insensitive to large-scale underdensity down to a threshold of roughly half the mean density. The differences in galaxy properties at the lowest global densities we can explore (n ≤ 0.5n0) may be explained by (1) a relative scarcity of the small-scale primordial density enhancements needed to form massive early-type/absorption-line galaxies and (2) present-day galaxy encounters that are relatively more effective because of the lower velocity dispersion on small scales (<200 h⁻¹ kpc) we observe in these regions. In the voids, where the luminous galaxies presumably formed more recently, there should be more gas and dust present for active star formation triggered by nearby companions.

Key words: galaxies: distances and redshifts — galaxies: fundamental parameters — galaxies: photometry — galaxies: statistics — large-scale structure of universe

1. INTRODUCTION

In the last decade, wide-angle redshift surveys have revealed large-scale structure in the local universe comprising coherent sheets of galaxies with embedded galaxy clusters, bounding vast (10⁵–10⁶ Mpc³) and well-defined "voids" where galaxies are largely absent. The influence of these structures' large-scale density environment upon galaxy properties has been a continuing source of debate and is of interest for constraining proposed models of galaxy formation and evolution. The morphology-density relation (see, e.g., Dressler 1980; Postman & Geller 1984), which quantifies the increasing fraction of elliptical and lenticular galaxies with local density, is one of the most obvious indicators of environmental dependence for densities greater than the mean. In the lowest density regions, the voids, the observational evidence of trends in morphological mix, luminosity distribution, star formation rate, etc., is still rudimentary because of the intrinsic scarcity of void galaxies and the difficulties in defining an unbiased sample for study. Here we use a broadband imaging and spectroscopic survey of a large optically selected sample to compare the properties of galaxies in voids with their counterparts in denser regions.

We refer the reader to the first paper of this study (Grogin & Geller 1999, hereafter Paper I) for a more detailed review of the previous theoretical and observational research into void galaxies, which we summarize here. Proposed theories of galaxy formation and evolution have variously predicted that the voids contain "failed galaxies" identified as diffuse dwarfs and Malin 1-type giants (Dekel & Silk 1986; Hoffman, Silk, & Wyse 1992), or galaxies with the same morphological mix as higher density regions outside clusters (Balland, Silk, & Schaeffer 1998), or no luminous galaxies at all for the want of tidal interactions to trigger star formation (Lacey et al. 1993). Some of these theories have already met serious challenge from observations that have shown that dwarf galaxies trace the distribution of the more luminous galaxies and do not fill the voids (Kuhn, Hopp, & Elsässer 1997; Popescu, Hopp, & Elsässer 1997; Binggeli 1989) and that the low surface brightness giants are rela-
tively rare and not found in the voids (Szomoru et al. 1996b; Bothun et al. 1993; Weinberg et al. 1991; Henning & Kerr 1989).

Most previous studies of void galaxies have focused on emission-line-selected and IRAS-selected objects in the Bootes void at $z \sim 0.05$ (Kirshner et al. 1981, 1987); all have been limited to a few dozen objects or fewer. The galaxies observed in the Bootes void (1) are brighter on average than emission-line galaxies (ELGs) at similar redshift and contain a large fraction (≈40%) with unusual or disturbed morphology (Cruzen, Weistrop, & Hoopes 1997); (2) have star formation rates ranging from 3 to 55 $M_\odot$ yr$^{-1}$, up to almost 3 times the rate found in normal field disk systems (Weistrop et al. 1995), in apparent contrast to the Lacey et al. (1993) model prediction; and (3) are mostly late-type gas-rich systems with optical and H $\alpha$ properties and local environments similar to field galaxies of the same morphological type (Szomoru, van Gorkom, & Gregg 1996a; Szomoru et al. 1996b).

Szomoru et al. (1996b) conclude that the Bootes void galaxies formed as normal field galaxies in local density enhancements within the void, and that the surrounding global underdensity is irrelevant to the formation and evolution of these galaxies. Because the Bootes void galaxies are not optically selected, though, their properties may not be representative of the overall void-galaxy population. On the other hand, similar conclusions were drawn by Thorstensen et al. (1995) in a study of 27 Zwicky catalog (CGCG, Zwicky et al. 1961–1968) galaxies within a closer void mapped out by the Center for Astrophysics Redshift Survey (CfA2, Geller & Huchra 1989). The fraction of absorption-line galaxies in their optically selected sample was typical of regions outside cluster cores, and the local morphology-density relation appeared to hold even within the global underdensity.

Our goal is to clarify the properties of void galaxies by collecting high-quality optical data for a large sample with well-defined selection criteria. We thus obtained multicolor CCD images and high signal-to-noise ratio spectra for ≈150 optically selected galaxies within prominent nearby voids. We work from the CfA2 redshift survey, which has the wide sky coverage and dense sampling necessary to delineate voids at redshifts $cz \lesssim 10,000$ km s$^{-1}$. These conditions are not met for the Bootes void, making the definition of Bootes void galaxies in previous studies harder to interpret.

Using a straightforward density estimation technique, we identified three large ($\sim 30–50$ h$^{-1}$ Mpc) voids within the magnitude-limited survey and included all galaxies within these regions at densities less than the mean ($n < \bar{n}$). In addition to the void galaxies from CfA2, we have also included fainter galaxies in the same regions from the deeper Century Survey (CS, Geller et al. 1997) and 15R Survey (Geller et al. 2000). We thereby gain extra sensitivity toward the faint end of the void-galaxy luminosity distribution, up to 3 mag fainter than $M_*$. Covering essentially the entire volume of three distinct voids, our sample should place improved constraints upon the luminosity, color, and morphological distributions and star formation history of void galaxies. Moreover, this optically selected sample should be more broadly representative than previous void-galaxy studies restricted to emission-line, IRAS-selected, and H $\alpha$-selected objects. We also conduct a follow-up redshift survey to $m_R = 16.13$ in our imaging survey fields and identify fainter void-galaxy companions, akin to the Szomoru et al. (1996a) H $\alpha$ survey for neighbors of the Bootes void galaxies. We thereby probe the small-scale (≤150 h$^{-1}$ kpc) environments around galaxies in regions of large-scale (5 h$^{-1}$ Mpc) underdensity. Here and throughout we assume a Hubble constant $H_0 \equiv 100$ h km s$^{-1}$ Mpc$^{-1}$.

In Paper I, we introduced the sample and its selection procedure, described the broadband imaging survey, and examined the variation of the galaxy luminosity distribution and color distribution with increasing large-scale underdensity. The luminosity distribution in modestly underdense void periphery regions ($1 < n/\bar{n} \leq 2$) and in modestly underdense regions (0.5 < n/\bar{n} ≤ 1) are both consistent with typical redshift survey luminosity functions (LFs) in B and R. However, galaxies in the lowest density regions (n/\bar{n} ≤ 0.5) have a significantly steeper LF ($\alpha \sim -1.4$). Similarly, the $B-R$ color distribution does not vary with density down to 0.5\bar{n}, but at lower densities the galaxies are significantly bluer.

Here we address the morphology and current star formation [as indicated by EW(H$\alpha$)] of optically selected galaxies in underdense regions. In addition, we describe a deeper redshift survey of the imaging survey fields designed to reveal nearby companions to the more luminous void galaxies. Section 2 reviews the void-galaxy sample selection briefly (cf. Paper I) and discusses the selection of redshift survey targets. We describe the spectroscopic observations and data reduction in § 3. We then analyze the morphological distribution (§ 4) and H$\alpha$ equivalent width distribution (§ 5) of the sample as a function of the smoothed large-scale (5 h$^{-1}$ Mpc) galaxy number density. Section 6 describes results from the redshift survey for close companions. We conclude in § 7.

2. SAMPLE SELECTION

Paper I contains a detailed description of the sample selection for the imaging and spectroscopic survey, summarized here in § 2.1. In § 2.2, we describe the selection procedure for a deeper redshift survey of the image survey fields to identify nearby companions of the sample galaxies.

2.1. Imaging and Spectroscopic Survey Sample

We use a 5 h$^{-1}$ Mpc–smoothed density estimator (Grogin & Geller 1998) to identify three prominent voids in the CfA2 redshift survey. We attempt to include all CfA2 galaxies below the mean density contour ($n < \bar{n}$) around the voids, as well as fainter galaxies in these regions from the 15R and Century Surveys. The apparent magnitude limit of the CS enables us to include void galaxies with absolute magnitude $R \lesssim -18$, some 3 mag fainter than $M_*$. By restricting our study to galaxies within three of the largest underdense regions in CfA2 (≥30 h$^{-1}$ Mpc diameter), we minimize the sample contamination by interlopers with large peculiar velocity. Table 1 lists the galaxy sample, including arcsecond B1950.0 coordinates, Galactocentric radial velocities, and the n/\bar{n} corresponding to those locations.

We define the galaxies in Table 1 with n/\bar{n} ≤ 1 as the “full void sample” (FVS). We further examine the properties of two FVS subsamples: the lowest density void subsample (LDVS) of 46 galaxies with n/\bar{n} ≤ 0.5, and the complementary higher density void subsample (HDVS) of 104 galaxies with 0.5 < n/\bar{n} ≤ 1. Our survey also includes some of the
TABLE 1

| Name            | R.A. (B1950.0) | Decl. (B1950.0) | \(cz\) (km \(s^{-1}\)) | Density* (\(n/\bar{n}\)) | \(r_{SE}\) * (mag) | \(T\) * (\(A\)) |
|-----------------|----------------|----------------|------------------------|-------------------------|-------------------|-----------------|
| IC 5378         | 00 00 03.98    | +16 21 56.9    | 6554                   | 1.19                    | 13.43             | -5              |
| 00012 +1555     | 00 01 10.32    | +15 54 30.2    | 6636                   | 1.14                    | 14.84             | -3              |
| 00017 +1030     | 00 01 39.12    | +10 30 42.5    | 8134                   | 0.91                    | 13.66             | 3               |
| NGC 7825        | 00 02 32.74    | +04 55 31.1    | 8220                   | 1.45                    | 13.81             | 3               |
| 00055 +0926     | 00 05 32.74    | +09 26 22.6    | 6606                   | 1.18                    | 13.29             | 3               |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Radial velocities are Galactocentric. Table 1 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

* Density uncertainty \(\leq 0.1\) (Grogin & Geller 1998).

SExtractor MAG_BEST (cf. §2.2).

B-band CCD morphology. Both Ir and Pec assigned \(T = 10\).

2.2. Void-Galaxy Field Redshift Survey Sample

Most of the volume spanned by the voids of interest has only been surveyed to the CfA2 magnitude limit, \(m_k \approx 15.5\). At the 5000–10,000 km \(s^{-1}\) distance of these voids, this limiting magnitude corresponds to an absolute magnitude cutoff of \(\sim B_\alpha\) or brighter. To gain information on the presence of fainter companions to the void galaxies in our study, we use the SExtractor program (Bertin & Arnouts 1996) to make a list of fainter galaxies on the R-band imaging survey fields. We define the SExtractor magnitude \(r_{SE}\) as the output MAG_BEST with ANALYSIS THRESH set to 25 mag arcsec\(^{-2}\) (see Bertin & Arnouts 1996). We limit the redshift survey to \(r_{SE} = 16.1\), the rough limit for efficient redshift measurement using the FAST spectrograph on the F. L. Whipple Observatory (FLWO) 1.5 m telescope. This magnitude limit is also commensurate with the Century Survey limit \((m_R = 16.13)\), as well as with the deepest 15R Survey fields in our study (see Paper I).

As a check on the reliability of SExtractor magnitudes, we compare against the isophotal photometry from our imaging survey of the Table 1 galaxies (Paper I). Those R-band magnitudes are determined at the \(\mu_R = 26\) mag arcsec\(^{-2}\) isophote; we denote them \(r_{B26}\). Figure 1 shows SExtractor magnitudes \(r_{SE}\) versus \(r_{B26}\) for 291 of the 296 galaxies in Table 1; the remaining five do not have SExtractor magnitudes, because of saturated R-band image pixels (00132 +1930, NGC 7311) or confusion with nearby bright stars (00341 +2117, 01193 +1531, 23410 +1123). We indicate the linear least-squares fit between the two magnitude estimates (dotted line), with 11 outliers at greater than 2 \(\sigma\) clipped from the fitting. Because Table 1 includes fainter 15R and Century Survey galaxies, we have good calibration down to the \(r_{SE} = 16.1\) limit of the companion redshift survey.

Figure 1 shows that the agreement between \(r_{SE}\) and \(r_{B26}\) is excellent over \(\approx 3.5\) mag. The scatter about the fit is only 0.05 mag, comparable to the uncertainty in the \(r_{B26}\) magnitudes (Paper I). The slope of the fit, \(dr_{B26}/dr_{SE} = 1.043 \pm 0.004\), indicates that the scale error is negligible. The crossover magnitude, for which \(r_{SE} = r_{B26}\), is 15.49 \(\pm 0.14\) mag. The linear fit is sufficiently well constrained that our \(r_{SE} = 16.1\) survey limit corresponds to a limiting \(r_{B26} = 16.13 \pm 0.01\). This value may be directly compared with the similarly calibrated 15R and Century \(r_{B26}\) limits given in Paper I. For the 5000–10,000 km \(s^{-1}\) redshift range of the three voids, this redshift survey therefore includes galaxies brighter than \(r_{B26} \approx -17.4\) to \(-18.9\). Here and throughout the paper, we leave off an implicit \(-5\log h\) when quoting absolute magnitudes.

The \(\approx 11\) imaging survey fields are roughly centered on the target galaxies—the absolute mean deviation of the pointing offset is \(\approx 30^\circ\). Given this mean offset and the
sample’s distribution of angular diameter distance, we estimate that the mean sky coverage of the redshift survey around the galaxies in Table 1 drops to 90% at a projected radius of \( \approx 115 h^{-1} \) kpc.

Table 2 lists the arcsecond B1950.0 coordinates and SExtractor magnitudes \( r_{SE} \) of the companion redshift survey targets (sorted by right ascension), as well as the angular separation of each from its respective “primary” (cf. Table 1). Some galaxies in Table 2 have multiple entries because their neighbor more than one primary. In some cases the neighbor is itself a primary from Table 1; we note this in the comment field. There are 211 unique galaxies in Table 2, which form 250 pairings with primaries from Table 1. Of these 250 pairs, 180 have projected separations \( \leq 115 h^{-1} \) kpc.

3. OBSERVATIONS AND DATA REDUCTION

Paper I describes the imaging survey and reductions in detail. The resulting CCD images from the FLWO 1.2 m reflector have typical exposure times of 300 s in R and \( 2 \times 300 \) s in B. Here we describe (1) a high signal-to-noise ratio (S/N) spectroscopic survey of the CGCG and 15R galaxies in the primary sample (cf. § 2.1) and (2) a deeper redshift survey of galaxies in the \( \sim 11' \) R-band fields of the imaging survey (cf. § 2.2).

3.1. High-S/N Spectroscopic Survey

We carried out the spectroscopic survey of CGCG galaxies in our sample with the FAST long-slit CCD spectrograph (Fabricant et al. 1998) on the FLWO 1.5 m Tillinghast reflector over the period 1995–1998. We used a 3” slit and a 300 line mm\(^{-1}\) grating, providing spectral coverage from 3600 to 7600 Å at 6 Å resolution. For the typical exposure times of 10–20 minutes, we obtained an S/N in the H\(\alpha\) continuum of \( \sim 30 \) per 1.5 Å pixel.

For the 15R galaxies in our sample, we used the 15R redshift survey spectra. These spectra were taken over the period 1994–1996 with FAST in an identical observing setup to our CGCG spectra. The exposure times for these spectra are typically 6–12 minutes, yielding an H\(\alpha\) continuum S/N of \( \sim 15 \).

The high-S/N spectroscopic survey of CGCG and 15R galaxies is essentially complete: 100% for the LDVS, 99% for the HDVS, and 98% for the VPS. Including the unobserved Century Survey galaxies in the accounting, the overall spectroscopic completeness is 98% for the LDVS, 95% for the HDVS, and 95% for the VPS.

All spectra were reduced and wavelength-calibrated using standard IRAF tasks as part of the CfA spectroscopic data pipeline (see Kurtz & Mink 1998). We flux-calibrate the resulting one-dimensional spectra with spectrophotometric standards (Massey et al. 1988; Massey & Gronwall 1990) taken on the same nights. Because these spectra were observed as part of the FAST batch queue, the observing conditions were not always photometric. We therefore treat the flux calibrations relative to absolute and only quote equivalent widths rather than line fluxes.

We next deredshift each spectrum using the error-weighted mean of cross-correlation radial velocities found with FAST-customized emission- and absorption-line templates (see Kurtz & Mink 1998; Grogin & Geller 1998). Our redshifts from the high-S/N CGCG spectra supersede the previous CfA redshift survey values and are reflected in the recent Updated Zwicky Catalog (UZC, Falco et al. 1999). We do not correct the spectra for reddening (intrinsic or Galactic), but note that the majority of sample galaxies are at high Galactic latitudes, where Galactic reddening is minimal. Figure 2 shows a representative subset of our reduced imaging and spectroscopic data: B-band images and corresponding spectra for a range of early- to late-type galaxies.

We make a first pass through the deredshifted spectra with SPLIT, fitting blended Gaussian line profiles to the Hz and N \( \pi\) lines and also fitting H\(\beta\) and H\(\delta\) for later Balmer absorption correction. We note that the FAST spectral resolution of 6 Å allows clean deblending of Hz \( \lambda \sim 6563\) from the adjacent [N \( \pi\)] \( \lambda \sim 6548, 6584\) lines. Using the first-pass line centers and widths, we make a second pass through the spectra to determine the equivalent widths and associated errors via direct line and continuum integration rather than profile fitting.

We apply an approximate correction to EW(H\(\alpha\)) for Balmer absorption by using the greater of EW(H\(\gamma\)) and EW(H\(\delta\)) if detected in absorption at \( \pm 1 \sigma\). We note that only one of the 277 galaxies in our spectroscopic sample has Balmer absorption exceeding 5 Å (CGCG 0109.0+0014), and this object has strong emission lines. There appear to be no \( E+A^*\) galaxies in our sample, which is not surprising given the small fraction (\( \sim 0.2\%\)) of such objects in the local universe (Zabludoff et al. 1996). Table 1 includes the resulting Hz equivalent widths and their errors.

3.2. Redshift Survey of Void-Galaxy Fields

We observed the redshift survey targets of Table 2 with the FAST long-slit CCD spectrograph (Fabricant et al. 1998) on the FLWO 1.5 m Tillinghast reflector over the period 1996 June–1997 November as part of the FAST

**TABLE 2**

Neighbors to Primary Galaxies in This Study

| R.A. (B1950.0) | Decl. (B1950.0) | \( c_z \) (km s\(^{-1}\)) | \( r_{SE} \) (mag) | Neighbor Primary \(^a\) | \( \Delta \theta \) (arcsec) | \( \Delta c_z \) (km s\(^{-1}\)) | Comments |
|---------------|----------------|-----------------|----------------|-----------------|-----------------|-----------------|---------|
| 00 00 04:01   | +16 22 24:2    | 5834 \pm 5      | 15.24          | IC 5378          | 27              | −515            | NED redshift |
| 00 00 06:89   | +16 19 18:5    | 6328 \pm 18     | 15.33          | IC 5378          | 163             | −21             |         |
| 00 02 53:21   | +04 53 52:8    | 5629            | 14.26          | NGC 7825         | 321             | −2426           | NED redshift |
| 00 05 14:45   | +09 25 53:4    | 15.43           | 00055+0926     | 272             |                 |                 |         |
| 00 05 56:50   | +09 56 06:7    | 15.18           | 00059+0956     | 46              |                 |                 |         |

Note.—Table 2 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

\( ^a\) SExtractor MAG\_BEST (cf. § 2.2).

\( ^b\) Name as given in Table 1.
Fig. 2—Representative sample of the spectroscopic and imaging survey data: long-slit spectra and $B$-band images for six galaxies spanning early to late morphologies. The spectra have been deredshifted and smoothed to the 6 Å FAST spectrograph resolution. Galactocentric velocities noted on the spectra determine the respective $20 \, h^{-1}$ kpc scale bars (for $q_0 = 0.5$).
FIG. 3.—Histograms of the revised morphological type $T$ for the VPS (top), the HDVS (middle), and the LDVS (bottom).

| Sample   | $N$  | $T < 0$ (%) | $0 \leq T \leq 5$ (%) | $T > 5$ (%) |
|----------|-----|-------------|------------------------|-------------|
| LDVS     | 46  | 15 ± 5      | 65 ± 7                 | 20 ± 6      |
| HDVS     | 104 | 27 ± 4      | 62 ± 5                 | 12 ± 3      |
| VPS      | 130 | 32 ± 4      | 58 ± 4                 | 9 ± 3       |

Note.—See Fig. 3 for histogram of $T$-types.

batch queue. The exposure times ranged from 5 to 20 minutes, with a median of 12 minutes. The observing setup, as well as the spectrum reduction, wavelength calibration, and redshift extraction, were identical to the high-S/N spectroscopic survey (§ 3.1).

Of the 211 galaxies in Table 2, we include new measurements for 83. Another 46 are members of the primary sample and thus have known redshifts. For the remainder, we obtained 35 redshifts from the 15R and Century Surveys, the UZC (Falco et al. 1999), ZCAT (Huchra et al. 1995), and
systems appears somewhat larger for the LDVS: establish the morphological similarity between the VPS and Geller (1998). Clearly, a larger sample is desirable to better reflect the same underlying morphological mix. These two

grams yields only a 7% probability that these two samples correspond. The probability of the null hypothesis that the VPS and HDVS morphological mix, with an early-type fraction of $B_{\text{top}}$ is 30% (Table 3). A $\chi^2$ test of these two histograms yields a 78% probability of the null hypothesis that the VPS and HDVS have a consistent underlying morphological distribution.

In contrast, Figure 3 shows that the morphological mix changes significantly at the lowest densities (LDVS). There is a notable increase in the fraction of Irr/Pec galaxies and a corresponding decrease in the early-type fraction (Table 3). A $\chi^2$ test between the VPS and LDVS morphology histograms yields only a 7% probability that these two samples reflect the same underlying morphological mix. These two samples are well separated in surrounding density—the uncertainty in the $5 \, h^{-1}$ Mpc density estimator is $\pm 0.1$ at the distance of the three voids in this study (Grogin & Geller 1998). Clearly, a larger sample is desirable to better establish the morphological similarity between the VPS and HDVS, and their morphological contrast with the LDVS.

The incidence of qualitatively disturbed or interacting systems appears somewhat larger for the LDVS: $\sim 35\% \pm 10\%$, compared with $\sim 20\% \pm 5\%$ for the galaxies at larger $n$. We show (Fig. 4) a mosaic of nine $B$-band images of LDVS galaxies that are probable interactions. Notable among these interacting void galaxies is the spectacular object IC 4553 (Arp 220), the prototype (and nearest) ultraluminous IR galaxy. An increase in disturbed galaxies at the lowest global densities seems counter-intuitive. We show (§ 6) that the effect may result from a low small-scale velocity dispersion in these regions.

5. **EW($H\alpha$)-DENSITY RELATION**

Figure 5 shows the cumulative distribution function (CDF) of $H\alpha$ equivalent width for the three different density regimes: the VPS (dashed curve), the HDVS (dotted curve), and the LDVS (solid curve). The similarity between the VPS and HDVS is evident, with a Kolmogorov-Smirnov (K-S) probability of 32% that the galaxies in these two density regimes have a consistent underlying distribution of EW($H\alpha$). Given the similar fraction of early-type galaxies in these two samples (Fig. 3), it is not surprising that we see a similar fraction of absorption-line systems ($\sim 35\%$). If this absorption-line fraction is representative of the overall survey at similar densities, then void-galaxy studies drawn from emission-line surveys miss roughly one-third of the luminous galaxies in regions of modest global underdensity. Figure 5 shows that there are galaxies even at $n \leq 0.5 \bar{n}$ with old stellar populations and no appreciable current star formation.

The shift toward late-type morphology in the LDVS (Fig. 3) is mirrored by a shift toward larger $H\alpha$ equivalent widths (Fig. 5). Absorption-line systems are less than half as abundant at $n \leq 0.5 \bar{n}$ ($\approx 15\%$ of the total); strong ELGs with EW($H\alpha$) $> 40$ Å are more than 3 times as abundant. The K-S probability of the LDVS and VPS representing the same underlying distribution of EW($H\alpha$) is only 0.4%. The probability rises to 3% between the LDVS and HDVS.

Figure 6 shows EW($H\alpha$) as a function of the galaxies’ $B-R$ colors—the shift toward bluer galaxies in the LDVS is clear (cf. Paper I). The red galaxies are predominantly absorption-line systems, with the notable exception of several galaxies in the LDVS with $B-R \gtrsim 1.2$ and EW($H\alpha$) $\gtrsim 20$ Å. Figure 7 displays these galaxies’ spectra and $B$-band images. Only two have bright nearby compan-

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1 The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
ions (CGCG 0017.5+0612 E, CGCG 1614.5+4231), but the others have possible faint companions. All appear to be disk systems, and the red colors probably result from internal reddening by dust; Balmer decrements are in the range 6.13 (see § 3.2). We determine the incidence of close companions as a function of density environment, examine the relationship between the presence of companions and the distribution of EW(Hα) versus density, and measure the velocity separation of the close companions as a function of $n/\bar{n}$.

6. VOID-GALAXY COMPANIONS

Here we discuss various results stemming from our deeper redshift survey of the imaging survey fields to $m_g = 16.13$ (see § 3.2). We determine the incidence of close companions as a function of density environment, examine the relationship between the presence of companions and the distribution of EW(Hα) versus density, and measure the velocity separation of the close companions as a function of $n/\bar{n}$.

6.1. Incidence of Close Companions and Effect on EW(Hα)

Figure 8 shows the projected separations (in $h^{-1}$ kpc) and absolute velocity separations for all entries in Table 2 with measured redshift. A galaxy in Table 2 counts as a companion if the velocity separation from the primary is less than 1000 km s$^{-1}$ (dashed line). This velocity cutoff is generous, but the gap in Figure 8 at $|\Delta z| \sim 500–2000$ km s$^{-1}$ leads us to expect few interlopers. Because the sky coverage of the neighbor redshift survey becomes increasingly sparse at projected separations $D_p \gtrsim 115$ $h^{-1}$ kpc (dotted line), we repeat the analyses in this section with and without the added companion criterion $D_p \leq 115$ $h^{-1}$ kpc.

Table 4 lists the fraction of galaxies in the different density groupings that are classified as “unpaired” (zero companions as defined above) and “paired” (at least one such companion), or cannot yet be classified because of one or more missing redshifts in Table 2. The fraction of paired galaxies decreases consistently across all density subsamples by ~25% under the restriction $D_p \leq 115$ $h^{-1}$ kpc. Table 4 shows that the fraction of paired galaxies is largely insensitive to the global density environment. Szomoru et al. (1996b), who detected 29 companions around 12 Bootes void galaxies in H I, also noted this tendency of void galaxies to be no less isolated on these small scales than galaxies at higher density.

We investigate the relationship between close companions and recent star formation in void galaxies by comparing EW(Hα) CDFs for paired versus unpaired galaxies. Figure 9 shows a dual-CDF plot of the paired and unpaired galaxies’ EW(Hα) (with the companion restriction $D_p \leq 115$ $h^{-1}$ kpc): the unpaired galaxies’ CDF increases from the bottom; the paired galaxies’ CDF decreases from the top. As in Figure 5, we distinguish between the VPS (dashed curve), HDVS (dotted curve), and LDVS (solid curve). The overall fraction of galaxies exceeding a given EW(Hα) is now represented by the interval between the upper and lower curves. For example, the excess of high-EW(Hα) galaxies in the LDVS is reflected here in the slower convergence of upper and lower solid curves until large EW(Hα). The upper and lower curves converge to the fraction of galaxies with EW(Hα) measurements but without detected companions. As the overall unpaired fraction is similar for each density subsample (see Table 4), it is reassuring that the three sets of curves converge at similar levels.

Inspection of the lower curves of Figure 9 reveals that the unpaired galaxies have much the same distribution of EW(Hα), regardless of the global density environment. The K-S probabilities (Table 5) confirm this impression. In con-

| Density Sample | Unpaired (%) | Paired (%) | Unknown (%) | $N_{pairs}$ | $\sigma_{cz}$ (km s$^{-1}$) |
|----------------|--------------|------------|-------------|------------|-----------------|
| LDVS:          |              |            |             |            |                 |
| $D_p \leq 115$ $h^{-1}$ kpc...... | 76 | 15 | 9 | 8 | 88 ± 22 |
| All $D_p$ ............... | 67 | 22 | 11 | 13 | 102 ± 20 |
| HDVS:          |              |            |             |            |                 |
| $D_p \leq 115$ $h^{-1}$ kpc...... | 68 | 20 | 12 | 30 | 203 ± 26 |
| All $D_p$ ............... | 61 | 28 | 12 | 39 | 183 ± 21 |
| VPS:           |              |            |             |            |                 |
| $D_p \leq 115$ $h^{-1}$ kpc...... | 69 | 22 | 9 | 36 | 266 ± 31 |
| All $D_p$ ............... | 63 | 28 | 8 | 64 | 231 ± 20 |

Note.—“Unpaired” galaxies have no other galaxy with $r_{SB} \leq 16.1$ and $\Delta z \leq 1000$ km s$^{-1}$ within the specified projected radius $D_p$; “paired” galaxies have at least one. The “unknown” fraction are unpaired but with at least one neighbor within the specified projected radius and lacking a redshift.

![Fig. 6.—Hα equivalent width vs. absolute B−R color for the VPS (top), the HDVS (middle), and the LDVS (bottom).](image-url)
Fig. 7.—Long-slit spectra and $B$-band images for the six LDVS galaxies with red colors ($B - R > 1.2$) and EW(H$\alpha$) $> 20$ Å. The spectra have been deredshifted and smoothed to the 6 Å FAST spectrograph resolution. Galactocentric velocities noted on the spectra determine the respective $10\ h^{-1}$ kpc scale bars (for $q_0 = 0.5$).
The redshift survey sky coverage is approximately 90% to a projected radius of 115 h⁻¹ kpc (dotted line). We only consider a pair to be associated if the velocity separation is less than 1000 km s⁻¹ (dashed line).

6.2. Pair Velocity Separation versus Density

Figure 10 shows the radial velocity separation Δcz versus projected separation for entries in Table 2 with |Δcz| < 1000 km s⁻¹. Clearly, the velocity separations of the LDVS pairs (triangles) are much smaller than either the HDVS pairs (squares) or the VPS pairs (stars). For the pairs that fall within the ≈90% coverage radius of 115 h⁻¹ kpc (dotted line), the dispersion in velocity separation σΔcz is 88 ± 22 km s⁻¹ for the LDVS, compared with 203 ± 26 km s⁻¹ for the HDVS and 266 ± 31 km s⁻¹ for the VPS (Table 4). These values for σΔcz do not vary by more than the errors if we include the points in Figure 10 with projected separations greater than 115 h⁻¹ kpc (“All Dₚ” in Table 4).

An F-test (Table 6) between the respective Δcz distributions for companions with Dₚ ≤ 115 h⁻¹ kpc yields a low probability P_F that the LDVS could have the same underlying Δcz variance as the HDVS (P_F = 3.2%) or the VPS (P_F = 0.59%). The difference between HDVS and VPS dispersions is not significant at the 2 σ level (P_F = 13%). The F-test probabilities using all Dₚ from Table 2 are almost identical (Table 6). We discuss the implications of the velocity dispersion variation in § 7.

7. SUMMARY AND CONCLUSIONS

Our B- and R-band CCD imaging survey and high-S/N long-slit spectroscopic survey of ~300 galaxies in and around three prominent nearby voids have enabled us to examine the morphologies and star formation history [in terms of EW(Hα)] as a function of the global density environment for n ≤ 2n. These studies complement our earlier examination of the luminosity and B − R color distributions of the same galaxies (Paper I). We have also described an additional redshift survey of projected “companions” to mₚ = 16.13 that probes the very local environments (≤ 150 h⁻¹ kpc) around these galaxies within globally (5 h⁻¹ Mpc) low-density regions.

| Density Samples | Overall (%) | Dₚ ≤ 115 h⁻¹ kpc | All Dₚ |
|-----------------|-------------|------------------|--------|
|                 | Unpaired (%)| Paired (%)       | Unpaired (%)| Paired (%) |
| P_K(SLDVS vs. VPS) | 0.43        | 13               | 0.073  | 40          | 0.084 |
| P_K(SLDVS vs. HDVS) | 2.8         | 75               | 0.010  | 65          | 1.9   |
| P_K(HDVS vs. VPS) | 32          | 4.7              | 20     | 31          | 0.73  |

Note.—“Unpaired” and “paired” as defined in Table 4.
Our analysis of the CCD B morphologies and Hz line widths reveals the following:

1. The distribution of galaxy morphologies varies little with large-scale (5 $h^{-1}$ Mpc) density environment over the range $0.5 < n/\bar{n} < 2$, with a consistent fraction of early types ($\approx 35\%$ with $T < 0$). The distribution of Hz equivalent widths, indicative of star formation history, is similarly invariant with large-scale density over this range.

2. At large-scale densities below half the mean, both the morphology and EW(Hz) distributions deviate at the 2–3 $\sigma$ level from the higher density subsamples. There is a reduction in the early-type fraction (down to $\approx 15\%$) and a corresponding increase in the fraction of irregular/peculiar morphologies. More of these galaxies show active star formation; even several of the redder galaxies ($B-R > 1.2$) have EW(Hz) $> 20$ Å. Many of the void galaxies, particularly at the lowest densities, show evidence of recent or current mergers or interaction.

The results here and in Paper I can be combined into a consistent picture of the trends in galaxy properties with large-scale underdensity. In Paper I, we showed that the luminosity function in the voids at $\geq 0.5\bar{n}$ is consistent with typical redshift survey LFs; at densities below $0.5\bar{n}$, the LF faint-end slope steepens to $\alpha \sim -1.4$. Recent studies point to a type-dependent galaxy LF with steeper faint-end slope for the late morphologies in the combined CfA2 and second Southern Sky Redshift Survey (SSRS2) (Marzke et al. 1998) and for the ELGs in the Las Campanas Redshift Survey (Bromley et al. 1998). We might therefore expect our morphological and spectroscopic distributions to vary little over the range $0.5 < n/\bar{n} \leq 2$ and to shift toward late types and ELGs at the lowest densities. This trend is exactly what we observe (see §4)

Furthermore, we found in Paper I that the $B-R$ color distribution of our sample at densities $\geq 0.5\bar{n}$ is consistent with the overall survey and shifts significantly toward the blue for $n \leq 0.5\bar{n}$. This trend is consistent with the observed shift at $n \leq 0.5\bar{n}$ toward late-type and high-EW(Hz) galaxies, which are typically bluer than early-type and absorption-line systems.

To ascertain whether these changes in galaxy properties below $n/\bar{n} \approx 0.5$ are caused by variations in the local redshift-space environments of these galaxies (within $\approx 150$ $h^{-1}$ kpc), we have carried out a deeper redshift survey of the imaging survey fields, to $m_g = 16.13$. The relative fraction of unpaired versus paired galaxies (paired galaxies are closer than $150$ $h^{-1}$ kpc projected and 1000 km s$^{-1}$ in redshift) does not significantly vary with the degree of global underdensity. Furthermore, the distribution of EW(Hz) for the unpaired galaxies varies little between our density subsamples. However, the galaxies at the lowest densities ($n/\bar{n} \leq 0.5$) that have companions are invariably ELGs. At higher global densities, roughly $\approx 20\%$ of the galaxies with companions are absorption-line systems. This difference in paired-galaxy EW(Hz) with density is significant at the 4 $\sigma$ level.

Our companion redshift survey further reveals that the pair velocity separation decreases significantly (3 $\sigma$) at the lowest densities, in support of theoretical predictions (e.g., Narayanan, Berlind, & Weinberg 2000) that within the voids the velocity dispersion among galaxies should decline. Because associated galaxies at smaller velocity separations should have more effective interactions, the excess strong ELGs and disturbed morphologies at global underdensities ($n \leq 0.5\bar{n}$) may be ascribed to local influences.

These results argue for a hierarchical galaxy formation scenario in which the luminous galaxies in higher density regions formed earlier than at much lower density (e.g., Kauffmann 1996). The older galaxies at higher density would typically have less gas and dust at the present epoch and thus show less active star formation even in the presence of nearby companions. In the voids, where the luminous galaxies presumably formed more recently, there should be more gas and dust present for active star formation triggered by nearby companions. As the EW(Hz) distributions are almost identical for the unpaired galaxies at different global density, we conclude that the local environment, i.e., the presence or absence of nearby ($\leq 150$ $h^{-1}$ kpc) companions, has more influence upon the current rate of star formation in these regions. In a future paper we hope to clarify the relationship between global underdensity and galaxy age (and metallicity) by studying the absorption-line indices of our high-S/N spectra (cf. Trager et al. 1998 and references therein). We may thereby use low-density regions to test the prediction by Ballard et al. (1998) that noncluster
elliptical galaxies must have all formed at high redshift (z \gtrsim 2.5). Although the sample of void galaxies described here is much larger than previous studies of at most a few dozen objects (e.g., Cruzen et al. 1997; Szomoru et al. 1996a; Thorstensen et al. 1995; Weistrop et al. 1995), the distinctions in galaxy properties we observe at the lowest densities are based upon fewer than 50 objects. We should like to increase the LDVS sample size to improve our statistics. One avenue is to include all other low-density portions of CfA2 and the comparably deep SSRS2 (da Costa et al. 1998). Unfortunately, the centers of voids are very empty, at least to and we would only expect to increase the low-density sample thereby to \( \sim 100 \) galaxies. Because the global density estimator requires a well-sampled, contiguous volume with dimensions \( \sim 5 \, h^{-1} \) Mpc, growing the LDVS significantly is contingent upon deeper, wide-angle redshift surveys such as the Sloan Digital Sky Survey (Bahcall 1995) and the 2dF Galaxy Redshift Survey (Folkes et al. 1999).

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