THE OPTICAL LUMINOSITY FUNCTION OF VOID GALAXIES IN THE SDSS AND ALFALFA SURVEYS

CRYSTAL M. MOORMAN1, MICHAEL S. VOGELEY1, FIONA HOYLE2, DANNY C. PAN3, MARTHA P. HAYNES4, AND RICCARDO Giovanelli4

1 Department of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA; crystal.m.moorman@drexel.edu
2 Pontificia Universidad Católica de Ecuador, 12 de Octubre 1076 y Roca, Quito, Ecuador
3 Shanghai Astronomical Observatory, Shanghai, China, 200030
4 Center for Radiophysics and Space Research, Space Sciences Building, Cornell University Ithaca, NY 14853, USA

Received 2015 May 4; accepted 2015 August 3; published 2015 September 3

Abstract

We measure the r-band galaxy luminosity function (LF) across environments over the redshift range 0 < z < 0.107 using the Sloan Digital Sky Survey (SDSS). We divide our sample into galaxies residing in large-scale voids (void galaxies) and those residing in denser regions (wall galaxies). The best-fitting Schechter parameters for void galaxies are \( \log \Phi^* = -3.40 \pm 0.03 \log(\text{Mpc}^{-3}) \), \( M^* = -19.88 \pm 0.05 \), and \( \alpha = -1.20 \pm 0.02 \). For wall galaxies, the best-fitting parameters are \( \log \Phi^* = -2.86 \pm 0.02 \log(\text{Mpc}^{-3}) \), \( M^* = -20.80 \pm 0.03 \), and \( \alpha = -1.16 \pm 0.01 \). We find a shift in the characteristic magnitude, \( M^* \), toward fainter magnitudes for void galaxies and find no significant difference between the faint-end slopes of the void and wall galaxy LFs. We investigate how low-surface-brightness selection effects can affect the galaxy LF. To attempt to examine a sample of galaxies that is relatively free of surface-brightness selection effects, we compute the optical galaxy LF of galaxies detected by the blind H\textsc{i} survey Arecibo Legacy Fast ALFA (ALFALFA). We find that the global LF of the ALFALFA sample is not well fit by a Schechter function because of the presence of a wide dip in the LF around \( M_r = -18 \) and an upturn at fainter magnitudes (\( \alpha \sim -1.47 \)). We compare the H\textsc{i} selected r-band LF to various LFs of optically selected populations to determine where the H\textsc{i} selected optical LF obtains its shape. We find that sample selection plays a large role in determining the shape of the LF.

Key words: cosmology: observations – galaxies: luminosity function, mass function – large-scale structure of universe – methods: data analysis – methods: statistical

1. INTRODUCTION

A critical measurement of the distribution of galaxies, which may be compared to galaxy formation and evolution models, is the galaxy luminosity function (LF): the number of galaxies per volume per luminosity. The shape of an LF is typically fit by a Schechter (1976) function described as a power law with faint-end slope \( \alpha \) and an exponential drop-off at the characteristic magnitude, \( M^* \). With the advent of deep, wide optical surveys, we now have sufficiently large samples of galaxies that allow us to study the LF of complete samples of galaxies across environments, colors, and morphological types.

Deep-redshift surveys have allowed measurements of the evolution of the LF with cosmic time (Ramos et al. 2011; Loveday et al. 2012; Martinet et al. 2014a; McNaught-Roberts et al. 2014). Measuring how the LF changes with galaxy morphology and color can support or reject theories on galaxy formation and evolution. For instance, the LF results of Driver et al. (2007) suggest that galaxies begin their lives with a pseudo-bulge-like structure and evolve into disk galaxies before becoming classic elliptical galaxies. Madgwick et al. (2002), Driver et al. (2007), Yang et al. (2009), and Tempel et al. (2011) find that the galaxy LF varies with both color and morphological type. Early-type galaxies typically have larger characteristic magnitudes and flatter faint-end slopes than do late-type galaxies. Similarly, red galaxies tend to have flatter faint-end slopes and slightly larger characteristic magnitudes than do blue galaxies. They also find that the bright end of the LF is characteristically determined by red and elliptical galaxies, while the faint end is dominated by blue and spiral galaxies.

Determining how galaxy color and galaxy type vary with environment gives us insight as to how large-scale structure affects the evolution of galaxies. For example, Tempel et al. (2011) find that the shape of the spiral galaxy LF is independent of environment. This implies that spiral galaxies in voids evolve no differently than do spiral galaxies in denser regions. They also find that the faint end of the elliptical galaxy LF steepens with increasing density. This effect is likely due to the presence of satellite galaxies that formed in the early universe and have since been tidally stripped, quenching star formation at later times. However, these authors only probe the environmental effects on the LF of galaxies down to \( M_r = -17 \).

Previous measurements of the galaxy LF dependence on large-scale structure range from void regions (Grogin & Geller 1999; Hoyle et al. 2005; Tempel et al. 2011), to groups (Eke et al. 2004; Yang et al. 2009), to clusters (De Propris et al. 2003; Durret et al. 2011; Martinet et al. 2014b; McNaught-Roberts et al. 2014). The environmental effects on the characteristic magnitude remain consistent across the literature: \( M^* \) becomes fainter with decreasing large-scale density. The environmental dependence of \( \alpha \) varies in the literature depending on the survey, redshift limits, magnitude limits, and methods used.

Previous estimates of the best-fit Schechter function faint-end slopes of the galaxy LF in voids are not well constrained. Estimates range from \( \alpha = -1.18 \pm 0.03 \) for a small sample of galaxies brighter than \( M_r = -14.5 \) (Hoyle et al. 2005) to \( \alpha = -0.98 \pm 0.02 \) for galaxies brighter than \( M_r = -17 \) (Tempel et al. 2011) to \( \alpha = -1.36 \pm 0.05 \) for galaxies brighter than \( M_r = -17 \) (McNaught-Roberts et al. 2014). In the dwarf
distribution models provide a statistical description of the number of luminous galaxies that occupy a halo of given mass: massive halos host “central” galaxies as well as less luminous “satellites,” while very low mass halos may host, at most, one central galaxy. The ΛCDM simulations predict that the characteristic mass of the dark-matter halo mass function shifts toward lower mass in low-density regions (Goldberg et al. 2005). Together, these results imply that faint galaxies in voids are likely to be “central” galaxies in their own halos, while faint galaxies in denser regions are likely to be satellites of more luminous galaxies. Additionally, the hydrodynamic simulations used in Sawala et al. (2014), which were tailored to match the conditions of the local group, imply that luminous, low-mass halos near “central” halos were probably once larger halos that formed stars in the early universe and have since been tidally stripped by neighboring halos. These results imply a relatively steep faint-end slope in dense regions. Other simulations predict varying environmental effects on the faint-end slope of the galaxy LF. For instance, Mathis & White (2002) predict a steeper faint-end slope in low-density regions, while Cui et al. (2011) predict that the faint-end slope in low-density regions is similar to that of high-density regions. Therefore, accurately measuring the shape of the faint end of the LF provides strong constraints for formation models of dwarf galaxies.

The observed galaxy LF slope is significantly shallower (α ∼ −1.3) than the predicted low-mass halo slope. For theory to match observations, the incorporation of feedback and photo-ionization effects is required in simulations to suppress star formation in galaxies at both the faint and bright ends. Current simulations (e.g., the Millennium Simulation, Springel et al. 2005) have incorporated star-formation quenching effects such that the outcome of the predicted LF matches current measurements of the observed LF. However, if the current measurements are underestimating the “true” faint-end slope of the galaxy LF, as predicted by Blanton et al. (2005), then the simulations may need to scale back the effects of feedback and photoionization to account for the presence of LSB galaxies.

In this paper, we present the environmental effects on the LF of optically selected galaxies from the Sloan Digital Sky Survey (SDSS) Data Release 7 (DR7) and HI selected galaxies from the Arecibo Legacy Fast ALFA (ALFALFA) Survey. In Section 2 we briefly discuss the data and void identification method and compare the properties of HI and optically selected samples. In Section 3 we discuss the methods used in this work. We present the optical LF of void and wall galaxies from SDSS DR7 galaxies, as well as the void and wall LFs of HI detections from the ALFALFA Survey, in Section 4. Here, we also discuss any differences between the optical LFs of HI and optically selected galaxies. We discuss the conclusions of our work in Section 5. Throughout this work, we assume Ω_m = 0.26 and Ω_Λ = 0.74 when calculating comoving coordinates and absolute magnitudes.

2. DATA

2.1. SDSS DR7

The SDSS (Fukugita et al. 1996; Gunn et al. 1998; Lupton et al. 2001; Strauss et al. 2002; Blanton et al. 2003) is a wide-field multicolor imaging and spectroscopic survey covering a quarter of the northern Galactic hemisphere in the five-band SDSS system: u, g, r, i, and z. Once each image is classified,
follow-up spectroscopy is done on galaxies with r-band magnitude \( r < 17.77 \). Spectra obtained through the SDSS are taken using two double-fiber-fed spectrographs and fiber plug plates covering a portion of the sky 1°.49 in radius with minimum fiber separation of 55 arcsec.

For the optical data in this work, we utilize the Korea Institute for Advanced Study Value-Added Galaxy Catalog (KIAS-VAGC) of Choi et al. (2010). The KIAS-VAGC catalog is based on the SDSS DR7 (Abazajian et al. 2009) spectroscopic targets in the main galaxy sample and contains 707,817 galaxies.

### 2.2. ALFALFA

The ALFALFA Survey (Giovanelli et al. 2005a, 2005b) is a large-area, blind extragalactic HI survey with sensitivity limits allowing for the detection of galaxies with HI masses down to \( M_{\text{HI}} = 10^6 M_{\odot} \) out to 40 Mpc. The most recent release of the ALFALFA Survey (\( \alpha = 0.40 \); Haynes et al. 2011), covers \( \sim2800 \text{deg}^2 \) across two regions in the northern Galactic hemisphere, called the Spring Sky (\( 0^\circ 30^\prime < \alpha < 1^\circ 30^\prime, 0^\circ 4^\prime < \delta < 1^\circ 6^\prime \) and \( 24^\circ < \delta < 28^\circ \)), and two in the southern Galactic Hemisphere, called the Fall Sky (\( 22^\circ < \alpha < 0^\circ 3^\prime, 14^\circ < \delta < 16^\circ \) and \( 24^\circ < \delta < 32^\circ \)). The HI detections in this catalog are categorized as either Code 1, 2, or 9. Code 1 objects are reliable detections with high signal-to-noise ratio (\( S/N > 6.5 \); Code 2 objects have \( S/N < 6.5 \) and coincide with optical counterparts with known redshift similar to the HI detected redshift; and Code 9 objects are high-velocity clouds.

To obtain the optical properties of the HI sources, we use the cross-reference catalog of 12,468 ALFALFA HI sources with the most probable optical counterpart from the SDSS DR7 supplied by Haynes et al. (2011). Because we are interested in each galaxy’s environment, we must limit our sample to objects found in the region accessible to the DR7 void catalog of Pan et al. (2012), the NGC region. We limit our sample to Code 1 detections within \( z < 0.05 \) because of radio frequency interference beyond this redshift range.

For our detections, we query the SDSS DR7 database to obtain all information needed for the analysis in this work, such as color, ICI, absolute magnitude, and surface brightness. Because we compare optically selected galaxy LFs to HI-selected galaxy LFs, we must remain consistent in how we determine absolute magnitudes, \( M_r \). Therefore, we K-correct the magnitudes and band-shift each HI source’s \( M_r \) to \( z = 0.1 \) using K-correct version 4.4 (Blanton & Roweis 2007), as done in the KIAS-VAGC. Because not all ALFALFA detections have optical spectroscopy, we adopt the 21 cm redshift for determining each galaxy’s comoving distance and r-band absolute magnitude. Approximately 200 of \( \sim7000 \) of the galaxies in the ALFALFA sample are matched to SDSS galaxies for which SDSS spectra were not taken. The differences between optical and HI redshifts are typically less than 50 kpc s\(^{-1}\). Only a handful of galaxies have HI-to-optical redshift differences in the range 50–200 kpc s\(^{-1}\). These differences are consistent with the velocity widths of \( M^* \) galaxies, so the effect on the faint-end slope of the LF will be negligible.

### 2.3. Creating the Void Samples

We classify all of our galaxies as void or wall detections by comparing the comoving coordinates of each to the void catalog of Pan et al. (2012). This void catalog uses the galaxy-based void-finding algorithm of Hoyle & Vogele (2002), VoidFinder (also see El-Ad & Piran 1997). We briefly discuss the algorithm here. In a map of SDSS DR7 galaxies with \( M_r < -20.1 \) in the northern Galactic hemisphere, we calculate each galaxy’s third-nearest neighbor. If the third-nearest neighbor is at least \( 7 \times 10^{-1} \text{Mpc} \) away, the galaxy is removed from the map and is considered a “potential void galaxy.” Once all “potential void galaxies” have been removed, VoidFinder grows spheres in the empty regions of the map. If a sphere has a minimum radius of \( 10 \times 10^{-1} \text{Mpc} \) and lies completely within the survey mask, it is considered a true void. We then place the “potential void galaxies” back into the map. If these “potential void galaxies” lie within one of the true void spheres, we classify it as a “void galaxy”; otherwise, we classify it as a “wall galaxy.” We compare the locations of all of our galaxies against the locations of the void spheres. If a galaxy lies within a large-scale void in this catalog, we classify the galaxy as a “void galaxy”; otherwise, we classify the galaxy as a “wall galaxy.”

The void catalog contains 1054 voids, the largest of which are \( \sim30 \times 10^{-1} \text{Mpc} \) in effective radius. The median effective radius of all voids within the catalog is \( \sim17 \times 10^{-1} \text{Mpc} \). See Pan et al. (2012) for further details regarding the statistical properties of the voids in SDSS DR7. Because we require each sphere to lie completely within the mask, we risk misclassifying true void galaxies along the edges as wall galaxies. From the optically selected sample, we identify 75,063 (21%) void galaxies and 274,436 (77%) wall galaxies within \( z < 0.107 \). The remaining galaxies (2%) lie along the survey edges and are excluded because of the potential misclassification issues.

Similarly, for the HI selected sample, we positionally compare each HI detection’s comoving coordinates to the void catalog. We identify 2611 (35%) void detections, 4566 (60%) wall detections, and 390 (5%) detections located near the survey edges.

For the sake of comparing the effects of the selection biases between the SDSS and ALFALFA samples, we make an optically selected subsample that we call SDSS\textsubscript{nearby}. For SDSS\textsubscript{nearby}, we limit ourselves to galaxies within \( z < 0.05 \). We further limit the sample to galaxies within \( 0^7\text{m} < R.A. < 16^\circ 30^\prime, 0^\circ 4^\prime < \delta < 16^\circ \) and \( 24^\circ < \delta < 28^\circ \), to ensure we only use galaxies within the same volume as our ALFALFA sample. We compare the magnitude-limited \( r < 17.6 \) SDSS\textsubscript{nearby} galaxy locations to the void catalog of Pan et al. (2012). We identify 7058 (25%) void galaxies, 20,148 (73%) wall galaxies, and 537 (2%) galaxies living near the survey edges. The reader should keep in mind that a “void” sample from an HI survey and a “void” sample obtained from an optical survey contain fundamentally different galaxies.

### 2.4. Comparing The HI and Optically Selected Samples

Previous studies on the types of galaxies typically found by blind HI surveys reveal late-type, mostly blue galaxies with high star-formation rates and specific star-formation rates (Toribio & Solanes 2009). Huang et al. (2012) provide an in-depth comparison of optically and HI selected samples and show that galaxies detected in HI tend to have low star-
formation efficiencies. Here we briefly compare the environmental differences of an $\text{H} \, \text{I}$ selected sample from the ALFALFA Survey and an optically selected sample from the SDSS catalog covering the same volume of sky (SDSS$_{\text{nearby}}$).

In Figure 1 we compare the optical $u-r$ color distribution of SDSS$_{\text{nearby}}$ (upper) and ALFALFA (lower) galaxies. We obtain galaxy colors using SDSS model magnitudes. The feature that is most evident is the deficiency of red galaxies in the ALFALFA sample compared to the SDSS sample. The void and wall SDSS color distributions are bimodal with the second peak appearing as a result of the highly populated red sequence, whereas the $\text{H} \, \text{I}$ color distributions are unimodal with only a slight presence of the red sequence in the ALFALFA wall sample. While a majority of the ALFALFA detections are blue, we notice the void population on average tends to be bluer than the wall population. Hoyle et al. (2012) notice a similar trend toward bluer colors in the SDSS void sample. In both survey samples, we notice significantly fewer red galaxies in the void populations than those in walls.

In Figure 2 we present the $r$-band absolute magnitude distributions of the SDSS$_{\text{nearby}}$ (upper) and ALFALFA (lower) samples. As shown in Hoyle et al. (2012), we see a shift toward fainter magnitudes in the SDSS void sample. The $\text{H} \, \text{I}$ void galaxy sample detects relatively more dwarf galaxies than does the optically selected sample. This is because the SDSS spectroscopic main galaxy sample is biased against faint, low-surface-brightness patchy galaxies, which are more easily detectable in an $\text{H} \, \text{I}$ survey. Because of the relative abundance of dwarf galaxies in the $\text{H} \, \text{I}$ sample, we suspect that the LF of ALFALFA galaxies will have a much steeper slope than the optically selected sample. We also see that the $\text{H} \, \text{I}$ selected wall galaxies are slightly brighter than the typical optically selected wall galaxies on average. A typical galaxy in a wall will experience gas stripping phenomena (tidal stripping, mergers, ram pressure stripping, and so on), thereby reducing the $\text{H} \, \text{I}$ fraction of its baryonic content. This reduced $\text{H} \, \text{I}$ fraction will contain just enough $\text{H} \, \text{I}$ to be detected by a radio survey for only the largest or brightest galaxies in the walls. We suspect that the shift toward brighter galaxies in the mean of the distribution of the ALFALFA wall sample compared to the SDSS$_{\text{nearby}}$ wall sample will result in the ALFALFA wall LF having a somewhat brighter characteristic magnitude than that of SDSS$_{\text{nearby}}$.

As galaxies evolve, they are thought to move from the blue cloud to the red sequence after star formation has been quenched. Galaxies in voids are typically less evolved—and, therefore, fainter and more gaseous—than similar-sized galaxies in walls. This makes void galaxies easy targets for radio surveys. As we will show later in Section 4.3.1, ALFALFA prefers less-evolved galaxies, regardless of environment.

3. METHOD

3.1. The Stepwise Maximum Likelihood (SWML) Method

The LF is a measure of the number of galaxies per Mpc$^3$ in a magnitude range $dM_r$ centered at magnitude $M_r$. For each measurement of the LF, we find the best-fit parameters of a Schechter (1976) function of the form

$$
\Phi(M_r) = 0.4 \ln 10 \Phi_\star 10^{0.4(M^* - M_r)(\alpha + 1)} \times \exp(-10^{0.4(M^* - M_r)}).
$$

We estimate the LF of our SDSS and ALFALFA void and wall samples using the SWML method of Efstathiou et al. (1988). For details on how we apply the method, see Moorman et al. (2014), in which we detail the two-dimensional version of the SWML. The SWML method does not retain information about the normalization of the LF; therefore, we adjust the amplitude according to the number density of the particular sample of interest. For each sample, the wall volume is estimated by taking the difference between the total volume of interest and the volume of the voids within. We estimate the
We estimate errors for each optical LF from three sources. The first source is Poisson error, which accounts for ~70% of the uncertainties in each bin. These errors affect the brightest and faintest ends more so than the intermediate-magnitude bins because we have less information in the outermost bins. That is, extremely bright galaxies are uncommon in the universe, and the faintest galaxies are difficult to detect beyond the very nearby universe.

The second source is the error in each bin introduced from the SWML method, described in Efstathiou et al. (1988). These errors account for about 30% of the total bin uncertainties. As with the Poisson errors, we have less information about the galaxy distribution in the brightest and faintest bins, making the uncertainties larger in these bins.

The third source is an error estimate accounting for the inhomogeneity of large-scale structure, using the jackknife method of Efron (1982). For this source of error, we divide our region of interest into 18 subregions and calculate the LF of the galaxy sample, excluding one of the 18 regions for each iteration. We estimate the variance in each bin after all iterations. The jackknife errors account for less than 1% of the total error. This suggests that the SWML method is relatively robust against large-scale structure.

4. RESULTS

4.1. LF of Void Galaxies in an Optically Selected Sample

We calculate the LF of our SDSS void and wall galaxies down to \( M_r \sim -13 \) using the methods outlined in Section 3. In Figure 3, we present our estimates of the void (red) and wall (black) galaxy LFs with the best-fitting Schechter functions. The parameters associated with the best-fit Schechter functions are \( \log \Phi^* = -3.40 \pm 0.03 \) \( \text{log}(\text{Mpc}^{-3}) \), \( M^* = -19.88 \pm 0.05 \), and \( \alpha = -1.12 \pm 0.02 \) for void galaxies, and \( \log \Phi^* = -2.86 \pm 0.02 \) \( \text{log}(\text{Mpc}^{-3}) \), \( M^* = -20.80 \pm 0.03 \), and \( \alpha = -1.16 \pm 0.01 \) for wall galaxies. An explanation of uncertainties may be found in Section 3.2. Much like the void and wall LF results found using a previous partial data release of the SDSS (Hoyle et al. 2005), we find about a one-magnitude shift in \( M^* \) toward fainter galaxies in voids. It is obvious from Figure 3 that the faint-end slopes of both the void and wall LFs are underestimated. For a more accurate estimation of the faint-end slopes, we fit a power law to the LF values fainter than \( M_r = -18 \). These power-law slopes correspond to a slope of \( \alpha = -1.25 \pm 0.02 \) for void galaxies and \( \alpha = -1.27 \pm 0.02 \) for wall galaxies. There is no statistically significant difference between the slopes of the void and wall LFs down to \( M_r \sim -13 \), indicating that there is no relative excess of void dwarfs compared to the wall distribution. This faint-end slope result is consistent with the predictions of Cui et al. (2011), whose simulations show that the faint ends of the LF should remain the same between the most underdense and overdense regions. This conflicts with the predictions of Mathis & White (2002), although these authors neglect SNe feedback and background UV radiation, which should be included when calculating the infall rate of cold gas for low-mass halos. The faint end of the void and wall LFs starts to stray from a classic Schechter function once we reach the dwarf regime \( (M_r > -17) \). This variation does not appear in the analysis of Tempel et al. (2011) because the authors exclude galaxies fainter than \( M_r = -17 \). Excluding these dwarf galaxies from our analysis, we find a faint-end slope that closely matches that of Tempel et al. (2011).

We notice a feature at the bright end \( (M_r = -20.1) \) of both the void and wall LFs: the void LF drops in amplitude, while the wall LF increases in amplitude. These features are an artifact of the void identification process. The void catalog is defined by a volume-limited sample corresponding to galaxies with \( M_r < -20.1 \). By defining the void catalog using galaxies brighter than this magnitude, we will see a significant decrease in the number of bright \( (M_r < -20.1) \) void galaxies and an increase in the number of bright wall galaxies.

4.1.1. Comparing to Previous Observations and Simulations

We have measured the galaxy LF in both voids and walls, where the wall environment is effectively an average over all higher density regions. Comparing the void and wall galaxy LFs reveals an expected shift toward fainter galaxies in voids, but does not reveal any dependence of the faint-end slope on large-scale underdensities. (Our finding that the void faint-end slope matches the wall faint-end slope is similar to the trend found in Moorman et al. (2014), in which we find that the low-mass slope of the void H i mass function (HIMF) closely matches the low-mass slope of the wall HIMF.) We suspect that the void faint-end slope closely matches the LF slope of all galaxies in denser regions averaged together (wall galaxies) for the following reason. Rojas et al. (2004) and Hoyle et al. (2012) show that void galaxies are generally blue, late-type galaxies, and Tempel et al. (2011) show that the faint-end slope of late-type galaxies does not vary with environment. Thus, one might expect the faint-end slope of the void galaxy LF to be an average of the slopes of LFs across denser environments, where we find both early- and late-type galaxies.

Comparing our void LF results with previous work on the LFs of galaxy groups and clusters reveals a nonmonotonic trend in \( \alpha \) with environment. We find the void regions have a faint-end slope around \( \alpha = -1.2 \) (which is consistent with an
earlier result in Hoyle et al. 2005). Croton et al. (2005) find that galaxies in regions with density contrast \(-0.5 < \rho < 0\) (isolated galaxies not associated with voids) have a flattened faint-end slope of \(\alpha \sim -1.0\). Additionally, Tavasoli et al. (2015) investigate the effects of local environment within voids on the shape of the LF; these authors estimate the LF of \(\sim 110\) galaxies in “sparsely” voids and 111 galaxies in “populous” voids brighter than \(M_r = -19\), making it difficult to truly compare the faint-end slopes with our work. Galaxies in denser environments, such as galaxy groups, tend to have flat faint-end slopes in the \(\alpha \sim -1.0\) to \(-1.2\) range, where the slopes increase with increasing group mass (Eke et al. 2004; Yang et al. 2009). The faint-end slopes of the composite LFs of galaxy clusters tend to range from \(\alpha \sim -1.2\) to \(-1.4\) (Valotto et al. 1997; De Propris et al. 2003; Croton et al. 2005; McNaught-Roberts et al. 2014). Put together, the overall trend of the faint-end slope with environment is average for voids, flattens for “field” galaxies, steepens with increasing mass in groups, and it either remains constant or steepens further when the large-scale density increases to the cluster regime.

The steepening trend among denser regions is consistent with predictions from the hydrodynamic simulations of Sawala et al. (2014), who find that dwarf halos closer to central galaxies typically had higher masses in the earlier universe, making the probability of star formation more likely. That is, galaxies are more likely to form in halos near denser regions than in isolated halos in the field. The steepening of \(\alpha\) with increasing density from the field to clusters corroborates this prediction.

### 4.2. LF of Void Galaxies in an H\textsc{i} Selected Sample

As mentioned earlier, the predicted halo mass function has a steep slope of \(\alpha = -1.8\), whereas the observed LFs (estimated here and in other works) have much shallower slopes of \(\alpha \sim -1.2\) to \(-1.3\). Blanton et al. (2005) show that the faint end of the LF can be steepened to \(\alpha \sim -1.5\) with the inclusion of low-luminosity/low-surface-brightness galaxies. To avoid the optical selection bias against low-surface-brightness galaxies, we estimate the optical LF of a sample of H\textsc{i} selected galaxies from the ALFALFA sample.

We divide the ALFALFA galaxy sample into void and wall galaxies and estimate the \(r\)-band LF presented in Figure 4. It is clear from the figure that the H\textsc{i} selected LFs are not well fit by a simple Schechter function, but for the sake of comparison between the LFs in this work and others, we provide the best-fitting parameters to a Schechter function found using a least-squares estimator. For the void sample, we estimate the best-fitting Schechter parameters to be \(\log \Phi^* = -4.43 \pm 0.09\) log (Mpc\(^{-3}\)), \(M^* = -20.74 \pm 0.18\), and \(\alpha = -1.20 \pm 0.05\). For the wall galaxy sample, we estimate \(\log \Phi^* = -3.71 \pm 0.04\) log (Mpc\(^{-3}\)), \(M^* = -20.77 \pm 0.09\), and \(\alpha = -0.84 \pm 0.05\). See Section 3.2 for an explanation of uncertainties. The curves in Figure 4 show the Schechter functions associated with these best-fit parameters; however, the Schechter fits underestimate both the bright and faint ends of the ALFALFA LFs.

At the bright end, the best-fit Schechter function predicts the characteristic magnitudes of both the void and wall samples to be too bright. To get a realistic sense of the shift in \(M^*\) between voids and walls, we fit only the bright end \((-22 < M_r < -18)\) of the LFs, revealing a shift in \(M^*\) toward fainter magnitudes in voids by about one-half of a magnitude (see the left panel of Figure 5). The direction of this shift is consistent with the shift in the dark matter halo mass function of the extended Press–Schechter theory (Goldberg et al. 2005). The magnitude of the shift is significantly less than the shift in the predicted halo mass function, as well as the shift in \(M^*\) of the SDSS LF found in the previous section. The reason for this smaller shift is that typically the brightest galaxies in denser regions have burnt through their cool gas, lost their gas during mergers, or had it stripped away via tidal stripping, ram pressure stripping, and so on. Therefore, a survey looking for cool neutral gas will detect the brightest galaxies within denser regions far less frequently than will an optically selected sample. While an optically selected spectroscopic sample may be biased against faint, low-surface-brightness galaxies, an H\textsc{i} selected sample is biased against massive, red galaxies.

At the faint end, the best-fitting Schechter function also severely underestimates the faint-end slopes of the void and...
into a bright end and faint end, separated at
of the SDSS and ALFALFA samples across environments. Each LF was split
by a Schechter function; from this function, we extract the characteristic
function. From this fit, we extract the faint-end slope parameter, \( \alpha \). The Astrophysical Journal, 810:108 (11pp), 2015 September 10

| Sample | LSS | \( M^* \) | \( \alpha \) |
|--------|-----|----------|--------|
| SDSS   | void | \(-19.32 \pm 0.03\) | \(-1.25 \pm 0.02\) |
| SDSS   | wall | \(-20.54 \pm 0.02\) | \(-1.27 \pm 0.02\) |
| SDSSnearby | void | \(-19.30 \pm 0.06\) | \(-1.31 \pm 0.04\) |
| SDSSnearby | wall | \(-20.55 \pm 0.03\) | \(-1.23 \pm 0.03\) |
| ALFALFA | void | \(-19.95 \pm 0.07\) | \(-1.49 \pm 0.03\) |
| ALFALFA | wall | \(-20.49 \pm 0.04\) | \(-1.52 \pm 0.05\) |

Notes. Best-fit power law and Schechter function parameters to the optical LFs of the SDSS and ALFALFA samples across environments. Each LF was split into a bright end and faint end, separated at \( M_f = -18 \). Each bright end was fit by a Schechter function; from this function, we extract the characteristic magnitude parameter, \( M^* \). Each faint end (\( M_f > -18 \)) was fit by a power-law function. From this fit, we extract the faint-end slope parameter, \( \alpha \).

wall LFs, estimating a much shallower slope than actually observed. To more accurately determine the faint-end slopes, we fit a power-law function to only the faint ends (\(-18 < M_f < -13\)) of the LFs. The new faint-end slopes of the HI selected LFs (shown in the right panel of Figure 5) are \( \alpha = -1.49 \pm 0.03 \) for voids and \( \alpha = -1.52 \pm 0.05 \) for walls. We see no statistically significant difference in the faint-end slopes of the void and wall LFs. The faint-end slopes of the ALFALFA void and wall LFs appear to be independent of the large-scale environment. We suspect this is largely due to the relatively large number of late-type galaxies (which generally dominate the faint end of the LF) present in the ALFALFA sample compared to massive, elliptical galaxies. Tempel et al. (2011) find that the LF of spiral galaxies is independent of environment, while the faint-end slope of the observed elliptical galaxy LF steepens with increasing large-scale densities.

To more directly compare the void and wall distributions of the HI and optically selected samples, we need to compute the optical LF of SDSS and ALFALFA galaxies over the same volume of sky. Therefore, we measure the LF of the SDSSnearby sample and estimate its characteristic magnitude and faint-end slope in the following way. For each sample (SDSS, SDSSnearby, and ALFALFA), we split each LF into bright and faint ends, divided at \( M_f = -18 \). The bright end is fit with a Schechter function, from which we obtain the sample’s characteristic magnitude, \( M^* \). Each faint end is separately fit with a power law, from which we obtain the faint-end slope of each LF. We provide these fits to the data in Table 1. Note that the \( M^* \) and \( \alpha \) parameters in the table are not the same related parameters estimated in Equation 1.

Two interesting comparisons arise from this table. The first comes from comparing the full SDSS and SDSSnearby fits, which gives us information on how the selected volume affects the shape of the LF. We find it interesting that reducing the area and redshift affects the void faint-end slope. The faint-end slopes of the full SDSS sample are more accurate because we are averaging over more structure. The large-scale structure within the nearby volume may be atypical of the full universe. The second comparison worth making is between the ALFALFA and SDSSnearby fits, which gives us information on how sample selection affects the shape of the LF. We see that using an HI selected sample produces a much steeper faint-end slope than does an optically selected sample. This is due mostly to the inclusion of extremely low luminosity galaxies in HI surveys. The SDSS photometry affects the main galaxy sample target selection. The selection process is biased against low-surface-brightness galaxies, so these faint galaxies are excluded from our optical sample. (Refer to Figure 2 for a comparison of the \( M_f \) distributions of the two samples.) The power-law fits to the faint-end slopes match closely those shown in Blanton et al. (2005), who investigate the effects of extremely low luminosity galaxies on the faint-end slope of the galaxy LF. Again, these authors find that the slopes increase from \( \alpha = -1.3 \) to \( \alpha = -1.5 \) when adjusting for the incompleteness of the SDSS spectroscopic sample at low surface brightnesses.

4.3. Comparing the Optically and HI Selected LFs

In Figure 6, we present the global LF of the Spring Sky subsample of the \( \alpha = 0.40 \) data set, as well as that of the SDSSnearby sample. We see in this figure, as well as in the previous subsection, that the optical LF of HI selected galaxies has a clearly different shape than that of the optically selected galaxies. The optically selected LF is reasonably well fit by a Schechter function with estimated parameters \( \log \Phi^* = -3.69 \pm 0.03 \), \( M^* = -20.75 \pm 0.05 \), and \( \alpha = -1.21 \pm 0.02 \). It is clear from the figure that the HI selected global LF is not fit well by a Schechter function. The best-fit Schechter parameters are \( \log \Phi^* = -4.21 \pm 0.05 \), \( M^* = -21.11 \pm 0.11 \), and \( \alpha = -1.10 \pm 0.03 \). One of the most notable aspects of the HI selected LF is a broad, dip-like feature around \( M_f = -18 \), followed by a sharp upturn at fainter magnitudes. Evidence of a similar dip and upturn is seen in Zwaan et al. (2001) in the LF of HI selected galaxies from the AHIISS, though the authors only use a sample of 60 HI sources and attribute the features of the faint-end slope to low-number statistics. For the first time, we show statistically significant evidence for a population of LSB dwarf galaxies present in the HI selected optical galaxy LF.

We suspect that the wide dip present in the ALFALFA LF is the result of a linear combination of different types of optically selected galaxies, that is, dwarfy starbursting galaxies at the faint end and gas-rich spirals at the bright end. In the next section, we will investigate different combinations of optically selected galaxies that may produce similar features and further split the HI sample to see which properties of the galaxies may

![Figure 6. LF of optically selected galaxies from SDSSnearby with the best-fit Schechter function (black) and the LF of HI selected galaxies from the \( \alpha = 0.40 \) Spring Sky with the best-fit Schechter function (red).](image-url)
The magnitude of the HI selected sample brighter than \( M_r = -18 \) shows a significant population of LSB dwarf galaxies not present in the SDSS main galaxy spectroscopic survey. The histogram (right panel) depicts the normalized SB distribution of ALFALFA galaxies with (dashed black) and without (orange) SDSS spectra. The dotted line denotes the LSB limit of Blanton et al. (2005), in which galaxies with \( SB > 23 \) are considered to be LSB detections.

Figure 7. Distribution of ALFALFA galaxies with (black) and without (orange) SDSS spectra in SB–\( M_r \) space. ALFALFA contains a significant population of LSB dwarf galaxies not present in the SDSS main galaxy spectroscopic survey. The histogram (right panel) depicts the normalized SB distribution of ALFALFA galaxies with (dashed black) and without (orange) SDSS spectra. The dotted line denotes the LSB limit of Blanton et al. (2005), in which galaxies with \( SB > 23 \) are considered to be LSB detections.

Knowing that most galaxies in an \( HI \) survey tend to be blue, late-type galaxies, we first split the SDSSnearby sample into blue and red galaxies using the color cut from Moorman et al. (2014): \( u - r = 0.09 \pm 0.06 \), where \( M_r \) is an object’s r-band absolute magnitude. We consider a galaxy with \( u - r \) color less than the value given by the equation to be blue; otherwise the galaxy is considered red. Our resulting subsamples contain 16,548 blue galaxies and 11,147 red galaxies. We estimate the LF of blue and red samples, and surprisingly, we find that the red galaxy LF produces a dip similar to, albeit much shallower than, that of the ALFALFA sample. See Figure 8 for the LFs of optically selected blue and red galaxies.

Suspecting that the red sample is composed of both large elliptical galaxies and edge-on spirals reddened by dust, we split the SDSSnearby red sample into two categories of morphological type. We make morphological cuts based on a galaxy’s ICI, which is shown to be correlated with morphological type (Shimasaku et al. 2001). The ICI is defined to be \( c_{in} = R_{50}/R_{90} \), where \( R_{50} \) and \( R_{90} \) are the radii containing 50% and 90% of the integrated Petrosian flux of a galaxy. In Figure 9 we present the normalized distribution of each sample’s color versus morphological type via the galaxies’ inverse concentration indices. It is clear from the figure that ALFALFA tends to detect fewer more-evolved galaxies than does SDSS, regardless of environment. Within the SDSSnearby sample, it appears that the void galaxies span the range of inverse concentration indices of ICI = 0.2–0.6, whereas the wall galaxies are primarily early-type galaxies (ICI < 0.42).

From the SDSSnearby sample, we have 8127 red elliptical galaxies and 3020 reddened spiral galaxies. As expected, we see in Figure 10 that splitting the red sample by ICI produces two distinct functions. The early-type galaxies have a relatively flat distribution with a small dip-like feature present around \( M_r = -18 \), while the late-type galaxies are well fit by a Schechter function with a faint-end slope similar to that of the global SDSS sample. The red, late-type galaxy LF has a characteristic magnitude similar to the blue galaxy LF, but it has a shallower slope. Zwaan et al. (2001) show that their H I selected LF closely matches that of late-type galaxies found in optical surveys. We find that this is not the case for the ALFALFA LF because of the significant population of massive...
gas-rich galaxies mentioned in Huang et al. (2012). See Figure 11 comparing the ALFALFA LF and the SDSSnearby late-type galaxy LF.

4.3.2. Subsets of the H I Selected LF

No known H I selection effects could be responsible for producing such a wide dip in the galaxy LF. In attempts to directly determine what populations of galaxies could be influencing the shape of the H I selected optical LF, we divide the ALFALFA sample by color into red (1376) and blue (2624) galaxies and compute the LFs. As shown in Figure 12, the dip in the LF remains present in the H I selected red galaxy sample, and we see a much less prevalent inflection at the same magnitude for the H I selected blue galaxy sample. Splitting the red and blue distributions by morphological type, based on ICI, does not reveal the origin of the dip feature present in the ALFALFA LF. That is, no subsample of ALFALFA galaxies removes the dip feature from the LF.

5. CONCLUSIONS

Using the SDSS DR7 void catalog obtained from Pan et al. (2012), the KIAS-VAGC SDSS DR7 galaxy catalog from Choi et al. (2010), and the ALFALFA α.40 catalog from Haynes et al. (2011), we measure the optical LF of 75,063 optically selected void galaxies with r-band magnitudes in the range $-22.0 < M_r < -13.0$ and 2,611 HI selected void galaxies with r-band magnitudes in the range $-22.0 < M_r < -13.0$. We find that sample selection plays a large role in determining the shape of the LF. Within a given data set, the large-scale environment affects the value of the characteristic magnitude of the LF, in that the characteristic magnitude shifts toward fainter values in cosmic voids. The environmental effects on the faint-end slope vary with the volume over which we look.

We find that the LF of void galaxies from the full SDSS sample is well fit by a Schechter function with parameters $\log \Phi^* = -3.40 \pm 0.03 \log (Mpc^{-3}), \ M^* = -19.88 \pm 0.05$. Figure 11.
and $\alpha = -1.20 \pm 0.02$. For galaxies residing in higher density regions, we find the best-fit Schechter parameters to be $\log \Phi^* = -2.86 \pm 0.02 \log(\text{Mpc}^{-3})$, $M^* = -20.80 \pm 0.03$, and $\alpha = -1.16 \pm 0.01$. Our findings suggest that the location of the LF is dependent on environment. That is, the characteristic magnitude, $M^*$, shifts to fainter magnitudes in voids. For the optically selected sample, the shift in $M^*$ is about one magnitude, consistent with an earlier partial SDSS data release (Hoyle et al. 2005). The direction of the shift is consistent with the extended Press–Schechter theory, which states that the dark-matter mass function should shift to lower masses in underdense regions (Goldberg et al. 2005). When we fit Schechter functions to the void and wall LFs over the range $-22.0 < M_r < -13.0$, we see a small environmental dependence on the faint-end slope Schechter function parameter. However, the best-fitting Schechter function underestimates the faint-end slope of the void and wall optical LFs. To account for this, we fit a power law to only the faint ends of the void and wall LFs (refer back to Table 1). We find that the true faint-end slope of the optically selected void galaxy LF is the same as that of the wall galaxy LF. It is important to note that the faint-end slope of the LF varies among isolated galaxies, groups, and clusters. The faint-end slope of the void LF matches the faint-end slope of all dense regions averaged together.

Limiting the SDSS sample to the volume over which $\alpha = 0.40$ and SDSS overlap (SDSSnearby) yields results similar to the full SDSS sample regarding $M^*$. That is, the characteristic magnitude in voids shifts fainter by about a full magnitude. However, we do see an environmental dependence on the faint-end slope when we fit a power law to the void and wall faint-end slopes. Over this reduced volume, the faint-end slope of void galaxies, estimated by a power-law fit to the faint end, steepens to $\alpha = -1.31 \pm 0.04$, as opposed to $\alpha = -1.23 \pm 0.03$ in walls. The difference in faint-end slopes in the SDSSnearby sample is due to the fact that we are not averaging over as much structure as in the full SDSS sample. The large-scale structure within the nearby volume is likely not representative of the full volume of the local universe; thus, we suspect that the full SDSS LF estimates are better representatives of the actual void and wall LFs of the local universe. The estimated faint-end slopes of galaxy LFs are highly dependent on the volume over which we observe, and we provide these results solely to compare the effects of sample selection on the optical LF.

The optical LF of ALFALFA galaxies within the $\alpha = 0.40$ Spring Sky region has a very wide, dip-like feature around $M_r = -18$; thus, the ALFALFA optical LF is not well fit by a Schechter function. We are currently unsure of the origin of the dip-like feature in the ALFALFA LF, but we suspect there may be a connection between the inclusion of massive, gas-rich galaxies in the ALFALFA sample and the bizarre shape. We do point out, however, that this feature cannot be explained by a simple combination of populations of optically selected galaxies. Splitting the HI sample by color, via SDSS model magnitudes, and by morphological type, via the ICI, reveals a significant population of late-type reddish galaxies. While the red elliptical galaxy LF from the SDSSnearby sample produced a relatively small dip around $M_r = -18$, the red elliptical population in ALFALFA is small compared to other galaxy types. Additionally, the dip feature is also seen in the ALFALFA blue galaxy LF. Thus, it is improbable that the red elliptical distribution alone caused the shape. The magnitude range over which we find this feature corresponds to a stellar mass range of $\log(M_h/M_\odot) \sim 8.5 - 9.5$. Huang et al. (2012) and Kreckel et al. (2012) find that specific star formation rates begin to decrease more substantially in galaxies with stellar masses greater than $M_h/M_\odot \sim 10^{9.5}$, but this does not explain the presence of the dip in the ALFALFA optical LF.

To estimate the ALFALFA void and wall galaxy LFs, we separately fit exponential cutoffs to the bright ends ($M_r < -18$) and power-law slopes to the faint ends ($M_r > -18$). The best-fit characteristic magnitude in voids is $M^* = -19.95 \pm 0.07$, and it is $M^* = -20.49 \pm 0.04$ for walls. We find a shift toward fainter magnitudes in voids of $\Delta M \sim 0.5$. This magnitude shift is much smaller than the full magnitude shift found in either SDSS sample because HI surveys detect bright galaxies in denser regions far less frequently than do optical surveys. The separately fit faint-end slopes of the ALFALFA galaxy LFs are $\alpha = -1.49 \pm 0.03$ for voids and $\alpha = -1.52 \pm 0.05$ for walls. Unlike the LFs of SDSSnearby galaxies over the same volume, we find no evidence for an environmental dependence on the faint-end slope parameter. This is likely because the HI selected sample primarily detects late-type galaxies, whose LFs were shown by Tempel et al. (2011) to be independent of large-scale environment.

We also see a much steeper faint-end slope than for the SDSSnearby sample. The effect of LSB galaxies present in the ALFALFA sample steepens the faint end of the optical LF closer to $\alpha \sim -1.5$, as predicted in Blanton et al. (2005). We believe this result is evidence that the “true” faint-end slope of the optical LF is around $\alpha \sim -1.5$. Thus, simulations may need to scale back the effects of feedback and photoionization to account for the presence of LSB galaxies. We also note that the presence of LSB galaxies in the ALFALFA sample is not the cause of the intriguing dip feature in the ALFALFA optical LF.

The authors would like to acknowledge the work of the entire ALFALFA collaboration team in observing, flagging, and extracting the catalog of galaxies used in this work. This study was supported by NSF grant AST-1410525. The ALFALFA team at Cornell is supported by NSF grants AST-0607007 and AST-1107390 to R.G. and M.P.H. and by grants from the Brinson Foundation.

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the participating institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U. S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS website is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium (ARC) for the participating institutions. The participating institutions are The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Korean Scientist Group, Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, University of Pittsburgh, Princeton University, the United States Naval Observatory, and the University of Washington.
REFERENCES

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543
Blanton, M. R., Lin, H., Lupton, R. H., et al. 2003, AJ, 125, 2276
Blanton, M. R., Lupton, R. H., Schlegel, D. J., et al. 2005, ApJ, 631, 208
Blanton, M. R., & Roweis, S. 2007, AJ, 133, 743
Choi, Y.-Y., Han, D.-H., & Kim, S. S. 2010, JKAS, 43, 191
Croton, D. J., & Farrar, G. R. 2008, MNRAS, 386, 2285
Croton, D. J., Farrar, G. R., Norberg, P., et al. 2005, MNRAS, 356, 1155
Cui, W., Springel, V., Yang, X., De Lucia, G., & Borgani, S. 2011, MNRAS, 416, 2997
De Propris, R., Colless, M., Driver, S. P., et al. 2003, MNRAS, 342, 725
Driver, S. P., Allen, P. D., Liske, J., & Graham, A. W. 2007, ApJL, 657, L85
Durret, F., Adami, C., & Laganá, T. F. 2011, in IAU Symp. 277, ed. C. Carignan, F. Combes & K. C. Freeman (Cambridge: Cambridge Univ. Press), 9
Efron, B. 1982, The Jackknife, the Bootstrap, and Other Resampling Plans (Philadelphia, PA: SIAM)
Efstathiou, G., Ellis, R. S., & Peterson, B. A. 1988, MNRAS, 232, 431
Eke, V. R., Frenk, C. S., Baugh, C. M., et al. 2004, MNRAS, 355, 769
El-Ad, H., & Piran, T. 1997, ApJ, 491, 421
Fukugita, M., Ichikawa, T., Gunn, J. E., et al. 1996, AJ, 111, 1748
Giovanelli, R., Haynes, M. P., Kent, B. R., et al. 2005a, AJ, 130, 2598
Giovanelli, R., Haynes, M. P., Kent, B. R., et al. 2005b, AJ, 130, 2613
Goldberg, D. M., Jones, T. D., Hoyle, F., et al. 2005, ApJ, 621, 643
Grogan, N. A., & Gallagher, J. J. 1999, AJ, 118, 2561
Gunn, J. E., Carr, M., Rockosi, C., et al. 1998, AJ, 116, 3040
Haynes, M. P., Giovanelli, R., Martin, A. M., et al. 2011, AJ, 142, 170
Hoyle, F., Rojas, R. R., Vogeley, M. S., & Brinkmann, J. 2005, ApJ, 620, 618
Hoyle, F., & Vogeley, M. S. 2002, ApJ, 566, 641
Hoyle, F., Vogeley, M. S., & Pan, D. 2012, MNRAS, 426, 3041
Huang, S., Haynes, M. P., Giovanelli, R., & Brinchmann, J. 2012, ApJ, 756, 113
Klypin, A. A., Trujillo-Gomez, S., & Primack, J. 2011, ApJ, 740, 102
Keeble, K., Platen, E., Aragón-Calvo, M. A., et al. 2012, AJ, 144, 16
Loveday, J., Norberg, P., Baldry, I. K., et al. 2012, MNRAS, 420, 1239
Lupton, R., Gunn, J. E., Ivezić, Z., Knapp, G. R., & Kent, S. 2001, in ASP Conf. Ser. 238, Astronomical Data Analysis Software and Systems X, ed. F. R. Hamden, Jr., F. A. Primini & H. E. Payne (San Francisco, CA: ASP), 269
Madgwick, D. S., Lahav, O., Baldry, I. K., et al. 2002, MNRAS, 333, 133
Martinet, M., Durret, F., Guennou, L., & Adami, C. 2014a, in SP2A-2014: Proc. Annual Meeting of the French Society of Astronomy and Astrophysics, ed. J. Ballet et al., 347
Martinet, N., Durret, F., Guennou, L., et al. 2014b, arXiv:1412.5821
Mathis, H., & White, S. D. M. 2002, MNRAS, 337, 1193
McNaught-Roberts, T., Norberg, P., Baugh, C., et al. 2014, MNRAS, 445, 2125
Moorman, C. M., Vogeley, M. S., Hoyle, F., et al. 2014, MNRAS, 444, 3559
Pan, D. C., Vogeley, M. S., Hoyle, F., Choi, Y.-Y., & Park, C. 2012, MNRAS, 421, 926
Papastergis, E., Cavuoti, A., Huang, S., Giovanelli, R., & Haynes, M. P. 2012, ApJ, 759, 138
Park, C., Choi, Y.-Y., Vogeley, M. S., et al. 2007, ApJ, 658, 898
Ramos, B. H. F., Pellegrini, P. S., Benoist, C., et al. 2011, AJ, 142, 41
Rojas, R. R., Vogeley, M. S., Hoyle, F., & Brinkmann, J. 2004, ApJ, 617, 50
Sawala, T., Frenk, C. S., Fattahi, A., et al. 2014, arXiv:1406.6362
Schechter, P. 1976, ApJ, 203, 297
Shimasaku, K., Fukugita, M., Doi, M., et al. 2001, AJ, 122, 1238
Springel, V., White, S. D. M., Jenkins, A., et al. 2005, Natur, 435, 629
Strauss, M. A., Weinberg, D. H., Lupton, R. H., et al. 2002, AJ, 124, 1810
Tavalesi, S., Rahmani, H., Khosroshahi, H. G., Vasei, K., & Lehner, M. D. 2015, ApJL, 803, L13
Tempel, E., Saar, E., Liivamägi, L. J., et al. 2011, A&A, 529, A53
Toribio, M. C., & Solanes, J. M. 2009, AJ, 138, 1957
Tully, R. B. 2005, in IAU Coll. 198, Near-fields Cosmology with Dwarf Elliptical Galaxies, ed. H. Jerjen & B. Binggeli (Cambridge: Cambridge Univ. Press), 531
Valotto, C. A., Nicotra, M. A., Muriel, H., & Lambas, D. G. 1997, ApJ, 479, 90
Yang, X., Mo, H. J., & van den Bosch, F. C. 2009, ApJ, 695, 900
Zwaan, M. A., Briggs, F. H., & Sprayberry, D. 2001, MNRAS, 327, 1249