PHOTOMETRIC SELECTION OF A MASSIVE GALAXY CATALOG WITH $z \geq 0.55$

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ABSTRACT

We present the development of a photometrically selected massive galaxy catalog, targeting Luminous Red Galaxies (LRGs) and massive blue galaxies at redshifts of $z \geq 0.55$. Massive galaxy candidates are selected using infrared/optical color–color cuts, with optical data from the Sloan Digital Sky Survey (SDSS) and infrared data from “unWISE” forced photometry derived from the Wide-field Infrared Survey Explorer (WISE). The selection method is based on previously developed techniques to select LRGs with $z > 0.5$, and is optimized using receiver operating characteristic curves. The catalog contains 16,191,145 objects, selected over the full SDSS DR10 footprint. The redshift distribution of the resulting catalog is estimated using spectroscopic redshifts from the DEEP2 Galaxy Redshift Survey and photometric redshifts from COSMOS. Restframe $U - B$ colors from DEEP2 are used to estimate LRG selection efficiency. Using DEEP2, the resulting catalog has an average redshift of $z = 0.65$, with a standard deviation of $\sigma = 2.0$, and an average restframe of $U - B = 1.0$, with a standard deviation of $\sigma = 0.27$. Using COSMOS, the resulting catalog has an average redshift of $z = 0.60$, with a standard deviation of $\sigma = 1.8$. We estimate 34% of the catalog to be blue galaxies with $z \geq 0.55$. An estimated 9.6% of selected objects are blue sources with redshift $z < 0.55$. Stellar contamination is estimated to be 1.8%.

Key words: catalogs – cosmology: observations – galaxies: distances and redshifts – galaxies: general – galaxies: photometry – methods: data analysis

1. INTRODUCTION

Luminous Red Galaxies (LRGs) are particularly suited to the study of clusters. These elliptical galaxies are typically the most luminous and massive galaxies at redshifts of $z \lesssim 1.0$, strongly tracing their underlying dark matter halos. Furthermore, their uniform spectral energy distribution (SED) and characteristic spectral features have allowed for simplified selection and accurate redshift determination at $z < 0.5$ (Eisenstein et al. 2001; Padmanabhan et al. 2005). This previous work takes advantage of a strong break in the SED of LRGs that occurs at 4000 Å. As objects at higher redshift are considered, however, this method becomes limited, as the 4000 Å feature passes into the $i$ band at $z \sim 0.75$. In order to efficiently select LRGs at higher redshifts, new techniques must be used.

This paper presents a publicly available catalog of massive galaxy candidates, with redshifts of $z \geq 0.55$. Galaxies are chosen based on photometric selection methods aimed to select higher redshift LRGs by combining optical and infrared surveys, developed by Schlegel et al. (2011) and further improved by Prakash et al. (2015). This work extends these previous results to include massive blue galaxies in addition to LRGs, and optimizes the selection cut using receiver operating characteristic (ROC) curves to target objects above $z \geq 0.55$.

The optical data used is from the Sloan Digital Sky Survey (SDSS; York et al. 2000) and infrared data used is from a catalog of forced photometry derived from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010; Lang et al. 2014). The resulting catalog’s redshift distribution is tested using spectroscopic and photometric redshifts, and restframe $U - B$ are used to determine LRG selection efficiency. A full description of the data sets used in this work is presented in Section 2. Selection technique and optimization are discussed in Section 3. The properties of the resulting catalog, and its comparison to similar work by Prakash et al. (2015), are described in Section 4.

2. DATA

2.1. SDSS/WISE Forced Photometry

Infrared and optical data used in this work are provided by the publicly available\textsuperscript{4} forced photometry catalog developed by Lang et al. (2014). The catalog provides improved photometry for WISE, at the positions of over 400 million primary sources from SDSS-III Data Release 10 (Eisenstein et al. 2011; Ahn et al. 2014). Taking advantage of the higher resolution of SDSS as a means to find sources in WISE, photometry is extracted using The Tractor image modeling code from “unWISE” unblurred coadds of WISE imaging. This unWISE imaging preserves the original resolution of the survey and allows for a higher signal-to-noise. For a detailed overview of the “unWISE” imaging, see Lang (2014). The resulting catalog provides a consistent set of sources between SDSS and WISE. Forced photometry may also be obtained for sources that, although blended in WISE, are resolved in SDSS.

The SDSS was conducted using a dedicated 2.5 m telescope at the Apache Point Observatory, New Mexico. The telescope is equipped with two multi-object spectrographs as well as a 120-megapixel wide-field camera (Gunn et al. 1998) performing 5-band $ugriz$ photometry at wavelengths 3551, 4686, 6165, 7481, 8931 Å (Fukugita et al. 1996; Gunn et al. 2006). To date, SDSS has made public 12 data releases (Abazajian et al. 2003, 2004, 2005; Adelman-McCarthy et al. 2006, 2007, 2008; Abazajian et al. 2009; Aihara et al. 2011; Ahn et al. 2012, 2014; Alam et al. 2015). This work uses the $r$ and $i$ bands.

\textsuperscript{4} http://unwise.me
WISE is a full-sky cryogenic survey, carried out in 2010 over four simultaneously observing bands centered at 3.4, 4.6, 12, and 22 μm. The survey achieved unprecedented sensitivity and angular resolution over the full sky; the most recent AllWISE data release attained 5σ point source sensitivities better than 0.054, 0.071, 0.730, and 5 mJy in unconfused regions on the ecliptic, where sources can be distinguished from background noise, as well as 6″1, 6″4, 6″5, and 12″0 angular resolution, in each of the four bands. For a full description of WISE, see Wright et al. (2010). This work uses the 3.4 μm (W1) band.

We use objects in the unWISE catalog that are marked as galaxies in the SDSS PhotoObj catalog files, with clean photometry flag set to 1. The catalog is then masked to ensure we are only using regions with good SDSS observing conditions: objects not contained within imaging masks provided by Ho et al. (2012) are excluded from the analysis. The photometry is then corrected for galactic extinction following Schlegel et al. (1998). Values of $E(B - V)$ are obtained from dust maps provided by Schlegel et al., and the extinction value $A(λ)$ for each band is calculated using $A/E(B - V)$ of 2.751, 2.086, and 0.234 for $r$, $i$, and $W1$, respectively. Extinction corrected magnitudes are then given by the apparent magnitude, subtracted by the extinction value.

In the optical, $r$ and $i$ band magnitudes are assumed to be consistent with AB magnitudes. In the infrared band, WISE apparent magnitudes are converted from Vega to AB magnitudes, using the following magnitude offset in the W1 band:

$$m_{AB} = m_{Vega} + 2.699.$$  

We limit the $r$, $i$, and $W1$ band (AB) magnitudes to 22.9, 21.8, and 20.5, respectively. Magnitude errors in each band are restricted to values below 0.2, corresponding to a 5 $σ$ detection. In regions of the surveys with shallower photometry, it is more difficult to reach this limit; these cuts perform best in regions with deeper photometry (e.g., Stripe 82).

### 2.2. DEEP2 Galaxy Redshift Survey

The DEEP2 Galaxy Redshift Survey is the second phase of the Deep Extragalactic Evolutionary Probe (DEEP) survey conducted using the Keck II telescope, utilizing the DEIMOS spectrograph (Faber et al. 2003). The most recent fourth data release contains all data from previous releases, providing spectra for ~50,000 galaxies, selected using BRI optical catalogs by Coil et al. (2004). The DEEP2 DR4 Redshift Catalog contains 50,319 unique entries with $0.0 < z < 1.4$, and covering 2.8 deg$^2$ over four separate 120′ by 30′ fields. In particular, we use the field centered at 14$h^{17}m^5$, +52°30′, coincident with the Extended Groth Strip (EGS). The redshift catalog also contains $U - B$ restframe colors obtained from Willmer et al. (2006). We consider redshift value $Z_{BEST}$, which is corrected for heliocentric motion, and restframe $U - B$ color, for sources with $QUALITY$ flag of 3 or 4 that are cross-matched to within 10′ of objects in the SDSS/WISE catalog. For more details on the DEEP2 survey, see Newman et al. (2013) and Davis et al. (2003, 2007).

Furthermore, we make use of a 2D selection function map of the EGS region to determine the completeness of the estimated properties of our sample. The map contains the probability that an object meeting the DEEP2 target-selection criteria is selected for observation and successfully yielded a redshift. The selection function maps are described in Cooper et al. (2006), Coil et al. (2008), and Newman et al. (2013).

### 2.3. COSMOS

#### 2.3.1. Photometric Redshift Catalog

The Cosmological Evolution Survey (COSMOS) Photometric Redshift Catalog is an accurate, magnitude-limited photo-z redshift catalog extending to $i < 25$. Redshifts are calculated using 30 bands in the UV (Galaxy Evolution Explorer), visible near-IR (Subaru, CFHT, United Kingdom Infrared Telescope, and National Optical Astronomy Observatory), and mid-IR (Spitzer/IRAC), over a 2 deg$^2$ region of the sky. For more information, see Ilbert et al. (2009).

We consider redshift value $z_{p, best}$ for sources that are cross-matched to within 10″ of objects in the SDSS/WISE catalog. To ensure reliable redshifts, we consider only objects in the photo-z catalog, where $flagB = 0$, $flagV = 0$, $flagI = 0$, $flagZ = 0$, and $flagD = 0$, to be sure that the objects are not masked in any optical band. Furthermore, we limit the photo-z catalog to $i^* < 24$.

#### 2.3.2. Zurich Structure and Morphology Catalog

We use star-galaxy classifications developed in the 2006 May release of Leauthaud et al. (2007), contained within the COSMOS Zurich Structure and Morphology catalog and described in Sargent et al. (2007) and Scarlata et al. (2007). We select a subset of the catalog, where $ACS\_CLEAN = 1$, and cross-match sources to within 10″ of objects in the SDSS/WISE catalog. The $ACS\_MU\_CLASS$ flag is used as an indicator of star-galaxy classification.

### 3. SELECTION

#### 3.1. Method

We seek to photometrically select a catalog of massive galaxies with redshift $z \geq 0.55$, building on the LRG selection technique described by Schlegel et al. (2011) and Prakash et al. (2015). Unable to rely on the 4000 Å spectral feature used in previous LRG selection techniques (e.g., Eisenstein et al. 2001), this new method takes advantage of the presence of cool, old stellar populations and low star formation of LRGs at $0.5 < z < 1$. At these redshifts, LRGs exhibit a spectral feature known as the “1.6 μm bump”. At restframe wavelength $λ_0 = 1.6 \mu m$, the SED of cool, old stars exhibit a local maximum due to a local minimum opacity of $H^+$ ions (John 1988); this is observable, for LRGs at redshifts $z \sim 0.5-1$, as a peak in infrared-to-optical flux at wavelengths of $\sim 2-4 \mu m$ (Sawicki 2002). Figure 1 shows an example LRG as observed in the $r$ and $W1$ bands. By combining optical and infrared imaging data, color–color cuts can therefore be made to select high-redshift LRGs.

Analysis by Schlegel et al. (2011) tests this selection technique using the All-Wavelength Extended Groth Strip (EGS) International Survey (AEGIS; Davis et al. 2007), which provides deep imaging data over all wavelengths in the EGS. The data set includes publicly available optical imaging from...
the Canada–France–Hawaii Telescope Legacy Survey (CFHT LS; Gwyn 2008), infrared imaging from the Spitzer Infrared Array Camera (IRAC; Barmby et al. 2008) and redshifts and restframe $U - B$ colors from the DEEP2 Redshift Survey (Davis et al. 2003) to test the selection technique.

The adopted method outlined in Schlegel et al. can be summarized in the simplest case as a direct cut in $r - [3.6 \mu m]$ versus $r - i$, both selecting LRGs at the desired redshift and eliminating galaxies with bluer SEDs. Here, $r$ and $i$ represent the optical $r$ and $i$ bands of the CFHT LS. The selection proposes $r$ and $i$ band cutoffs of 22.5 and 21.5, respectively, and yields 420 objects per square degree with $m_{[3.6 \mu m]} < 18.9$ and 1120 objects per square degree with $m_{[3.6 \mu m]} < 19.4$, based on a 0.4 deg$^2$ area within the EGS, with 10%–15% uncertainty due to cosmic variance.

As described by Schlegel et al. (2011), the lowest band in $WISE$ at 3.4 $\mu$m is particularly suited to this color–color cut, as it coincides with the 1.6 $\mu$m bump at $z \sim 1$. Furthermore, a cut in this $r - [3.4 \mu m]$ versus $r - i$ color–color space also allows for the separation of stars and galaxies, in order to select a catalog with low stellar contamination.

Prakash et al. (2015) presents a thorough analysis of these methods using optical photometry from CFHT LS, and infrared photometry from $WISE$. The cut was optimized to select LRGs with $z > 0.6$, by varying the intersection of a vertical line with a sloped line using the ROC curve and Figure of Merit (FOM) statistics. The result of this analysis can be summarized by two requirements:

$$
r - i > 0.98
$$

$$
r - [3.4 \mu m] > 2.0 \times (r - i).
$$

The analysis in Prakash et al. (2015) is intended to be used for target selection of LRGs in spectroscopic surveys such as the Extended Baryon Oscillation Spectroscopic Survey (eBOSS) and the Dark Energy Spectroscopic Instrument (DESI) survey. For further details on eBOSS target selection of LRGs using these cuts, see Prakash et al. (2016).

The work presented in this paper uses extinction corrected infrared data from the 3.4 $\mu$m band of $WISE$ forced photometry and extinction corrected $r$ and $i$ bands from SDSS. Model magnitudes are used to calculate $r - i$. In the case of $r - [3.4 \mu m]$, however, the treated as pointsource flag from Lang et al. (2014) indicates which $r$ band magnitude to use. If $WISE$ objects were treated as point sources for the purposes of forced photometry, we use PSF magnitudes in the $r$ band. For those that are treated as extended objects, we use composite model (cmodel) magnitudes in the $r$ band.

In Figure 2, the final selection cut is shown, as well as star-galaxy separation. The color–magnitude diagram of Figure 3 shows the separation of red and blue sequence galaxies with restframe $U - B$. In Figure 4, we show how the restframe $U - B$ vary across the color–color space, where restframe $U - B > 1.0$ are indicative LRG-like SED.

### 3.2. Optimization

We optimize the selection method to select a sample with redshift $z \geq 0.55$, and to extend the cut to allow for massive...
blue galaxies, while maintaining low stellar contamination. To identify the optimal color–color cut, we use ROC curves (True Positive Rate versus False Positive Rate). This curve provides a useful statistic to measure the performance of a binary classifier as a threshold is varied. Here, the classifier is a simple cut in color space, using the $U - B$ color space, using the COSMOS star-galaxy classification described in Section 2.3.2.

A “true positive” is defined as an object that has been correctly selected by the classifier, whereas a “false positive” is an object that has been incorrectly selected by the classifier. In this case, an object that is selected by the color–color cut and has an observed redshift $z \geq 0.55$ is a true positive; an object that is selected by the color–color cut and has an observed redshift $z < 0.55$ is a false positive. The “true positive rate” (also “completeness”) is the proportion of true positives to the total number of objects being classified that have redshift $z \geq 0.55$. The “false positive rate” is the proportion of false positives to the total number of objects being classified that have redshift $z < 0.55$. We use 1360 objects from the unWISE catalog cross-matched to DEEP2 spectroscopic redshifts within 10″ (shown in Figure 4) to estimate the redshifts of objects selected or rejected by the cut.

We select two intersecting lines in this color–color space, varying them systematically to optimize the resulting cut for our targeted redshift range. First, we fit an initial guess line (Line 1) whose purpose is to minimize stellar contamination on the right-hand side of the plot. Figure 2 shows the distribution of stars and galaxies in the color–color space, using the COSMOS star-galaxy classification described in Section 2.3.2.

Next, we fit a second line (Line 2) with some slope $m$, which will intersect with Line 1 at some value of $r - i$. For each value of $m$, we can find the optimal $r - i$ of intersection between the Line 1 and Line 2, by varying the point of intersection from $[-0.5, 2.0]$ and generating a ROC curve. The optimal intersection between the two lines corresponds to the value of $r - i$ for which the distance from (0,1) in the ROC curve space is minimized. We loop over the range of $m$, finding the best $r - i$ for each. Slope $m$ varies clockwise, from just below the horizontal to vertical. The optimal piecewise function for each slope tested, and their ROC curves, are shown in Figure 5.
To select the best classifier, we can compare the area under each ROC curve, as a better classifier will have an area closer to one. The optimal color–color cut is the one whose area under the ROC curve is largest. Lastly, we repeat this entire optimization process with Line 1 shifted slightly upward and downward, again comparing the area under the ROC curve to identify the best classifier. The optimized classifier, targeting $z \geq 0.55$, corresponds to the cut shown in Figure 2: Line 2 with slope $m = 0.249$. Line 1 shifted downward by 0.2 from our initial guess, and the point of intersection between Line 1 and Line 2 at $r - i = 1.17$.

We show the performance of this classifier against various redshift thresholds in Figure 6 and note that it performs slightly better for $z \geq 0.5$. We also show how the classifier varies if requiring different target redshifts in Figure 7. Lastly, we note that the area under the ROC curve is higher, i.e., the classifier performs better, if we also require targeted objects to have restframe $U - B > 1.0$. However, for the purposes of this work, we deliberately include bluer galaxies in addition to LRGs.

4. PROPERTIES OF SELECTED OBJECTS

16,191,145 massive galaxy candidates are selected over the full SDSS DR10 footprint, yielding a density of approximately 1426 objects per square degree. Figure 8 shows the distribution of these selected objects along the sky.

4.1. Redshift Distribution

We cross-match the resulting catalog with both DEEP2 spectroscopic redshifts and COSMOS photometric redshifts within 10" to test the efficiency of the cut. The resulting normalized redshift distributions are shown in Figure 9, alongside the redshift distribution of objects rejected by the selection method.

In the DEEP2 EGS field, we require cross-matched objects to lie within the 2D selection function map at values above 0.60. This allows for 82% completeness for 434 cross-matching massive galaxy candidates. The mean redshift is found to be $z = 0.65$, with $\sigma = 0.20$, and the median redshift is found to be $z = 0.64$. Contamination of selection rule for $z < 0.5$, $z < 0.55$, and $z < 0.6$ are 17%, 31%, and 42%, respectively.

Completeness of selection rule for $z > 0.5$, $z > 0.55$, and $z > 0.6$ are 68%, 72%, and 72%, respectively.

In the COSMOS field, we are able to cross-match 1793 photometric redshifts to the selected galaxies, with 94% completeness. The mean redshift is found to be $z = 0.60$, with $\sigma = 0.18$, and the median redshift is found to be $z = 0.60$. Contamination of selection rule for $z < 0.5$, $z < 0.55$, and $z < 0.6$ are 27%, 42%, and 51%, respectively. Completeness of selection rule for $z > 0.5$, $z > 0.55$, and $z > 0.6$ are 70%, 72%, and 74%, respectively.

4.2. U – B Restframe Color

We use restframe $U - B$ colors contained in the DEEP2 Redshift Galaxy Survey catalog to determine LRG selection efficiency. Figure 9 shows the distribution of $U - B$ for selected and rejected objects. Average restframe $U - B = 1.0$, with $\sigma = 0.27$, and median $U - B = 1.1$. Blue galaxies make up an estimated 44% of the catalog. Figure 10 shows the targeted properties of redshift and $U - B$ plotted together. Blue sources below the target redshift make up an estimated 9.6% of the catalog.

4.3. Stellar Contamination

Stellar contamination is estimated using the ACS_MU_CLASS flag contained within the COSMOS Zurich Structure & Morphology Catalog described in Section 2.3.2. Over the COSMOS area, 1,648 objects are cross-matched to within 10" of the selected objects, with a completeness of 98%. We estimate a stellar contamination of 1.8%.

4.4. Comparison to Previous Work

We include, for comparison, the selection cut developed by Prakash et al. (2015), shown in Figure 2. The cut performs best for a threshold of $z \geq 0.6$, and yields a more peaked redshift distribution closer to $z = 0.68$. In Figure 9, we show the resulting redshift distribution by Prakash et al. (2015) applied to our data. However, as seen in Figure 9, the cut presented in this work does not reject as many massive blue galaxies. Because the cut is wider, we are also able to select a much larger number of galaxies.
5. CONCLUSION AND FUTURE WORK

We have efficiently selected a catalog of massive galaxies optimized to select objects with $z \geq 0.55$, using optical and infrared photometry. In DEEP2, the resulting catalog has an average redshift of $z = 0.65$, with a standard deviation of $\sigma = 0.20$. In COSMOS, the resulting catalog has an average redshift of $z = 0.55$, with a standard deviation of $\sigma = 0.27$.

A Figure 8. Distribution of selected 16,191,145 LRG candidates along the full SDSS DR10 footprint. Figure produced using HEALPix (http://www.w3.org/1999/xlink) projection with NSIDE = 512(64^2 resolution), in equatorial coordinates. Area per pixel is 1.31 $\times$ 10^{-2} deg^2. Average density is 1426 selected objects per degree squared.

A Figure 9. Normalized redshift and restframe $U-B$ distributions of selected and rejected objects, and comparison to Prakash et al. (2015). The selection cut developed in this work provides a higher number of objects than the cut by Prakash et al. (2015), and does not exclude bluer galaxies, which are above the targeted redshift. Left column: spectroscopic redshift distribution of objects cross-matched with the DEEP2 EGS field. The histogram shows 531 selected objects targeting $z \geq 0.55$, 438 selected objects targeting $z \geq 0.70$, and 167 selected objects utilizing the cut proposed by Prakash et al. (2015). Center column: photometric redshift distribution of objects cross-matched with the COSMOS Photo-Z catalog. The histogram shows 1793 selected objects targeting $z \geq 0.55$, 1441 selected objects targeting $z \geq 0.70$, and 407 selected objects utilizing the cut proposed by Prakash et al. (2015). Right column: restframe $U-B$ distribution of objects cross-matched with the DEEP2 EGS field. The histogram shows 531 selected objects targeting $z \geq 0.55$, 438 selected objects targeting $z \geq 0.70$, and 167 selected objects utilizing the cut proposed by Prakash et al. (2015). Restframe $U-B$ distribution is used as an indicator of LRG selection efficiency.
The catalog is made of up bluer sources with redshifts of $z < 0.55$. Moreover, the selection yields a higher number of galaxies than previous work by Prakash et al. (2015). Stellar contamination is estimated to be 1.8%.

We anticipate a large signal from cross-correlations with CMB lensing, detections of the Sunyaev–Zel’dovich effect, and the Integrated Sachs–Wolfe effect. The catalog will be publicly available.

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REFERENCES

Abazajian, K., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2003, AJ, 126, 2081
Abazajian, K., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2004, AJ, 128, 502
Abazajian, K., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2005, AJ, 129, 1755
Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543
Adelman-McCarthy, J. K., Agüeros, M. A., Allam, S. S., et al. 2006, ApJS, 162, 38
Adelman-McCarthy, J. K., Agüeros, M. A., Allam, S. S., et al. 2007, ApJS, 172, 634
Adelman-McCarthy, J. K., Agüeros, M. A., Allam, S. S., et al. 2008, ApJS, 175, 297
Ahn, C. P., Alexandroff, R., Allende Prieto, C., et al. 2012, ApJS, 203, 21
Ahn, C. P., Alexandroff, R., Allende Prieto, C., et al. 2014, ApJS, 211, 17
Aihara, H., Allende Prieto, C., An, D., et al. 2011, ApJS, 193, 29
Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, ApJS, 219, 12
Barmby, P., Huang, J.-S., Ashby, M. L. N., et al. 2008, ApJS, 177, 431
Coil, A. L., Newman, J. A., Croton, D., et al. 2008, ApJ, 672, 153
Coil, A. L., Newman, J. A., Kaiser, N., et al. 2004, ApJ, 617, 765
Cooper, M. C., Newman, J. A., Croton, D. J., et al. 2006, MNRAS, 370, 198
Davis, M., Faber, S. M., Newman, J., et al. 2003, Proc. SPIE, 4834, 161
Davis, M., Guhathakurta, P., Konidaris, N. P., et al. 2007, ApJL, 660, L1
Eisenstein, D. J., Annis, J., Gunn, J. E., et al. 2001, AJ, 122, 2267
Eisenstein, D. J., Weinberg, D. H., Agol, E., et al. 2011, AJ, 142, 72
Faber, S. M., Phillips, A. C., Kibbick, R. L., et al. 2003, Proc. SPIE, 4841, 1657
Fukugita, M., Ichikawa, T., Gunn, J. E., et al. 1996, AJ, 111, 1748
Górski, K. M., Hivon, E., Banday, A. J., et al. 2005, ApJ, 622, 759
Gunn, J. E., Carr, M., Rockosi, C., et al. 1998, AJ, 116, 3040
Gunn, J. E., Siegmund, W. A., Mannery, E. J., et al. 2006, AJ, 131, 2332
Gwinn, S. D. J. 2008, PASP, 120, 212
Ho, S., Cuesta, A., Seo, H.-J., et al. 2012, ApJ, 761, 14
Ilbert, O., Capak, P., Salvato, M., et al. 2009, ApJ, 690, 1236
John, T. L. 1988, A&A, 193, 189
Lang, D. 2014, AJ, 147, 108
Lang, D., Hogg, D. W., & Schlegel, D. J. 2016, AJ, 151, 36
Leauthaud, A., Massey, R., Kneib, J.-P., et al. 2007, ApJS, 172, 219
Newman, J. A., Cooper, M. C., Davis, M., et al. 2013, ApJS, 208, 5
Padmanabhan, N., Budavári, T., Schlegel, D. J., et al. 2005, MNRAS, 359, 237
Prakash, A., Licquia, T. C., Newman, J. A., et al. 2016, ApJS, 224, 34
Prakash, A., Licquia, T. C., Newman, J. A., & Rao, S. M. 2015, ApJ, 803, 105
Sargent, M. T., Carollo, C. M., Lilly, S. J., et al. 2007, ApJS, 172, 434
Sawicki, M. 2002, AJ, 124, 3050
Scarlata, C., Carollo, C. M., Lilly, S., et al. 2007, ApJS, 172, 406
Schlegel, D., Abdalla, F., Abraham, T., et al. 2011, arXiv:1106.1706
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Waskom, M., Botvinnik, O., Hobson, P., et al. 2014, seaborn, v0.5.0, Zenodo, doi:10.5281/zenodo.12710
Willmer, C. N. A., Faber, S. M., Koo, D. C., et al. 2006, ApJ, 647, 853
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
York, D. G., Adelman, J., Anderson, J. E., Jr., et al. 2000, AJ, 120, 1579