THE LUMINOSITY FUNCTION OF MORPHOLOGICALLY CLASSIFIED GALAXIES IN THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

The morphological dependence of the luminosity function is studied, using a sample containing approximately 1500 bright galaxies classified into Hubble types by visual inspection, for a homogeneous sample obtained from the Sloan Digital Sky Survey northern equatorial stripes. Early-type galaxies are shown to have a characteristic magnitude 0.45 mag brighter than that of spiral galaxies in the r^* band, consistent with the “universal characteristic luminosity” in the B band. The shape of the luminosity function differs rather little among different morphological types: we do not see any symptoms of the sharp decline in the faint end of the luminosity function for early-type galaxies at least 2 mag fainter than the characteristic magnitude, although the faint-end behavior shows a slight decline (α ≲ −1) compared with the total sample. We also show that the rather flat faint-end slope for early-type galaxies is not due to an increasing mixture of dwarf galaxies, which have softer cores. This means that there are numerous faint early-type galaxies with highly concentrated cores.

Key words: cosmology: observations — galaxies: fundamental parameters

1. INTRODUCTION

The origin of the morphology of galaxies is a long-standing issue that could provide a key to discerning among models of the formation of galaxies. How galaxy morphology changes as a function of look-back time is perhaps the prime approach to this problem, and knowledge of the morphological dependence of the local luminosity function at zero redshift is the baseline. One specific example of the issues involved is whether the luminosity function of elliptical galaxies obeys a Schechter-type function, with a rather flat faint end (see, e.g., Marzke et al. 1994; Kochanek et al. 2001), or a Gaussian function, as inferred by Binggeli, Sandage, & Tammann (1988) and more recently by Bernardi et al. (2003b). If the latter is correct, one would envisage galaxy morphology as a bulge luminosity sequence (Dressler & Sandage 1983; Meisels & Ostriker 1984), which in turn provides a clue about the formation of elliptical galaxies and bulges.

There are also a number of uses for the morphology-dependent luminosity function (MDLF). We mention only one example: the frequency of gravitational lensing of quasar images is approximately proportional to the luminosity density of early-type galaxies, rather than to that of all galaxies (Fukugita & Turner 1991). The uncertainty in the MDLF is the largest source of error in predicting the frequency of gravitational lenses and, thus, in inferring the cosmological constant from such analyses.

Our understanding of the MDLF is significantly poorer than that of the luminosity function for galaxies in general, which has seen substantial progress in recent years (Folkes et al. 1999; Blanton et al. 2001) by virtue of large galaxy samples. The traditional way to obtain the MDLF is to use a morphological classification based on visual inspection of the images (Binggeli et al. 1988; Loveday et al. 1992; Marzke et al. 1994, 1998; Kochanek et al. 2001). Some modern studies have attempted to use spectroscopic features to classify galaxies into morphological types (Bromley et al. 1998; Folkes et al. 1999), which makes it possible to analyze large samples. Although a general correlation is known between spectroscopic and Hubble morphologies, the samples derived from the two methods are considerably different. In particular, classification using spectroscopic features or colors is sensitive to small-scale star formation activity now or in the recent past in early-type galaxies, while Hubble morphology is insensitive to this process. The problem of automated classification always lies in the difficulty of finding quantitative measures that strongly correlate with the Hubble sequence based on visual inspections. In this paper, we derive the MDLF based on visual classifications using a homogeneous bright-galaxy sample from the Sloan Digital Sky Survey (SDSS; York et al. 2000). The sample we use in this paper is small, but it is based on a homogeneous morphological classification with accurate photometry.

The SDSS conducts both photometric (Gunn et al. 1998; Hogg et al. 2001; Pier et al. 2003) and spectroscopic observations and is producing a homogeneous data set that is suitable for studies of galaxy statistics. The initial survey observations were made in the northern and southern equatorial stripes and produced a galaxy catalog to r^* = 22.5 mag in five color bands (Fukugita et al. 1996),...
with a photometric calibration that uses a new standard-star network observed at the US Naval Observatory (Smith et al. 2002). Spectroscopic follow-up is made to 17.8 mag with accurately defined criteria for target selection (Strauss et al. 2002). Our study is limited to bright galaxies, with $r^* \leq 15.9$ mag after Galactic extinction correction, since visual classifications sometimes cannot be made confidently beyond this magnitude with the SDSS imaging data. We have classified all galaxies satisfying this magnitude criterion in the northern equatorial stripe. The total number of galaxies in our sample is 1875, of which 1600 have spectroscopic information.

The bulk of the data we use have already been published as part of the Early Data Release (EDR; Stoughton et al. 2002). Our present work primarily uses the EDR but is supplemented by observations that are not included in the EDR, to make the sample as complete as possible. Photometry of galaxies in this region is discussed in a galaxy number-count paper by Yasuda et al. (2001), and the luminosity function has been derived by Blanton et al. (2001), who also discuss spectroscopic details.

2. THE SAMPLE AND MORPHOLOGICAL CLASSIFICATION

The region of the sky we consider is the northern equatorial stripe (SDSS photometry runs 752 and 756), covering $145^\circ < \alpha < 235^\circ$ and $|\beta| < 1^\circ$ ($J2000$), which is included in the EDR sample. The total area is 229.7 deg$^2$. We apply a Galactic extinction correction using the extinction map of Schlegel, Finkbeiner, & Davis (1998), assuming $A_r = A_r/E(B-V) = 2.75$, and we select galaxies with Petrosian magnitudes $r^*_p \leq 15.9$ after the correction in the automatically generated photometric catalog (Stoughton et al. 2002). We use the extinction-corrected Petrosian magnitude throughout this paper.

The photometric catalog yields 2418 galaxy candidates with $r^*_p \leq 15.9$ if we follow the criteria given by Strauss et al. (2002). This sample still contains a number of double stars and shredded galaxies because of deblending failures, which cannot be rejected by the automated algorithm. After visual inspection of all galaxy candidates, we obtain 1875 galaxies, of which 1600 (85%) are included in the spectroscopic sample. Spectroscopy was performed using 50 plugged plates, with an additional 41 plates centered in the neighboring stripes. These plates cover 228.1 deg$^2$. The confidence level for the redshift determination is mostly over 99%, but nine galaxies are given low (<85%) confidence, and we omit these from our sample. We also drop 38 galaxies that either contain multiple galaxies or have poor photometry as a result of deblending failures. This leaves 1553 galaxies. We note that there are some galaxies that are dropped from the primary galaxy selection in the photometric catalog (Yasuda et al. 2001; Strauss et al. 2002) because of saturation flags caused by nearby bright stars or for other reasons. We estimate that we have probably missed about \(\approx 88\) galaxies in our field from the rate of missed galaxies given in Yasuda et al. (2001). So, the overall sample completeness is estimated to be 79.5%. For a more detailed discussion of the spectroscopic sample, see Blanton et al. (2001).

All galaxies in our sample (1875) are classified into seven morphological classes, $T = 0$ (corresponding to Hubble type E), 1 (S0), 2 (Sa), 3 (Sb), 4 (Sc), 5 (Sd), and 6 (Im). Morphological classification was carried out by two of us (M. F. and O. N.) using the $g^*$-band image of each galaxy as displayed with the SAOImage viewer, according to the Hubble Atlas of Galaxies (Sandage 1961). We also refer to morphological types given by the Third Reference Catalogue of Bright Galaxies (RC3; de Vaucouleurs et al. 1991), so that our classification closely matches the traditional scheme, although the RC3 classification, which is based on photographic material, occasionally proves incorrect when galaxies are viewed as CCD images, which we can look at using different levels of brightness and contrast. We give an index of $-1$ when we cannot assign a morphological type. The classification from the two independent visual inspections agrees to within $\Delta T \leq 1.5$ for most galaxies, and a mean $0.5$ step in $T$ is taken for our final classification.

We reclassify galaxies into three groups, $0 \leq T \leq 1$ (E–S0), $1.5 \leq T \leq 3$ (S0/a–Sb), and $3.5 \leq T \leq 5$ (Sbc–SD). The morphological distribution of the galaxies in the different samples is given in Table 1. The ratio (E–S0):(S0/a–Sb):(Sbc–Sd):Im $\approx$ 0.40:0.34:0.24:0.02. This is somewhat larger than the $E$-S0 fraction, compared with the value usually adopted, because of our use of $r^*$ as the primary passband. For the same reason, the fraction of Im galaxies is smaller by a factor of 2–3 than that from $B$-selected samples. In this work, we do not divide the morphology into further detailed classes, given the uncertainty in visual classification, especially between E and S0 for fainter galaxies. We consider galaxies with $T > 5$ separately, since the spectroscopic target selection is biased against low surface brightness galaxies, and the relatively low quality of photometry for this class of galaxies makes the incompleteness significant; the completeness fraction of Im galaxies as read from Table 1 is only 54%, compared with \(\approx 83\%\) for the other classes. Along with a small Im fraction, our sample for an appropriate redshift range is too small to derive a reliable MDLF for Im galaxies.

### Table 1: Morphologically Classified Sample

| Sample | $0 \leq T \leq 1$ | $1 < T \leq 3$ | $3 < T \leq 5$ | $5 < T \leq 6$ | $T = -1$ | Total |
|--------|------------------|----------------|----------------|----------------|----------|-------|
|        | (E and S0)       | (S0/a–Sb)     | (Sbc–Sd)      | (Im)           | (Unclas.) |       |
| 1. Photometric sample | 740 | 630 | 444 | 35 | 26 | 1875 |
| 2. Spectroscopic sample | 630 | 545 | 381 | 23 | 21 | 1600 |
| 3. Sample with good photometry | 617 | 539 | 373 | 21 | 12 | 1562 |
| 4. Sample with $z > (85\% \text{ CL})$ | 616 | 538 | 369 | 19 | 11 | 1553 |
| 5. Sample used in MDLF | 597 | 518 | 350 | (10) | (7) | 1482 |
| 6. Sample used to obtain $\phi^*$ | 314 | 368 | 253 | (5) | ... | 894 |

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Note: $r^*$ is the Petrosian magnitude, $A_r$ is the extinction coefficient, and $E(B-V)$ is the extinction depth.
3. MORPHOLOGY-DEPENDENT LUMINOSITY FUNCTIONS

We show in Figure 1 the differential number counts of galaxies. The slope of the counts is slightly steeper than that of the Euclidean value and is in agreement with previous studies (Yasuda et al. 2001). The counts for the spectroscopic galaxies (dashed line) follow those of the photometric sample to within 1 $\sigma$ of Poisson statistics, so the completeness correction for the present sample does not depend on brightness.

We use the recession velocity with respect to the Galactic standard of rest as given by the RC3. We select galaxies in the redshift range $3000 \text{ km s}^{-1} < v < 36000 \text{ km s}^{-1}$. The lower cutoff is imposed to avoid large effects from peculiar velocity flow, and the upper cutoff is practically the limit of our sample. We further impose a cut on apparent magnitude of $r^* > 13.2$, since very bright galaxies are often dropped from spectroscopic targets. These selections exclude 71 galaxies from our sample, leaving 1482 galaxies with which to estimate the MDLF. The redshift distributions of our galaxy sample are shown in Figure 2, where the curves show the expectation for a homogeneous universe with the MDLF derived in this paper.

We compute MDLFs for the samples with three methods: maximum likelihood (ML; Sandage, Tammann, & Yahil 1979), stepwise maximum likelihood (SWML; Efstathiou, Ellis, & Peterson 1988), and the $V_{\text{max}}$ method. We take the luminosity step to be 0.25 mag for SWML. We adopt $\Omega = 0.3$ and $\lambda = 0.7$ for the cosmology, although the maximum redshift of our sample is $z = 0.12$ and the results hardly depend on the cosmological parameters. The $K$-correction is taken from Fukugita, Shimasaku, & Ichikawa (1995) with an interpolation with respect to $g^* - r^*$ color for each galaxy.

The results from the first two methods, ML and SWML, show good agreement, but those from the $V_{\text{max}}$ method differ from the former two at the faint end. This is a well-known effect generally ascribed to inhomogeneous galaxy distributions in redshift space, as are visible in Figure 2. In Figure 3, we present the MDLF from ML and SWML in the $r^*$ passband, together with the absolute magnitude distribution of galaxies used in the analysis. The ML estimate assumes a Schechter function,

$$\phi(L) dL = \phi^* \left( \frac{L}{L^*} \right)^{\alpha} \exp \left[ - \left( \frac{L}{L^*} \right) \right] dL,$$

(1)

and the derived parameters are given in Table 2, where we take the Hubble constant to be $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$. Only a crude estimate (with ML) is presented for the luminosity function for Im galaxies, since our sample is too small. We also present the results for the total sample, which includes not only galaxies with $T = 0-6$, but also those that could not be classified ($T = -1$). This is a bright-galaxy version of the analysis given by Blanton et al. (2001).

In this table we also give the luminosity densities obtained by integrating equation (1) from $L = 0$ to $L = \infty$. Contours of 1 and 2 standard deviation errors calculated from the likelihood functions are shown in the $\alpha - M^*$ plane in Figure 4. We have also carried out a jackknife error estimate, by dividing the sample into 10 right ascension bins (width of $\sim 1^\circ$), in order to study the effect of the sample variance. The best-fit values for the subsamples all fall within the 1 $\sigma$ ellipse given above, and the variance estimated from the jackknife method is smaller than the error we quoted. So, we adopt 1 $\sigma$ of the fit for our final error estimate.
We then assign an additional 0.05 mag error from the calibration of the photometry (added in quadrature). For more discussion about errors and selection effects, see Blanton et al. (2001). The errors expected from a number of items seen in their analysis are significantly smaller than the statistical error we are concerned with here.

We determine the normalization $\phi^*$ of the MDLF following the method of Efstathiou et al. (1988) for each sample of morphologically classified galaxies. We adopt the region of $M_r^*$ where the sample contains a sufficient number of galaxies, dropping those that are too bright ($M_r^* > M_r^* + 2$) and too faint ($M_r^* < M_r^* - 2$) and those with high redshifts to avoid strong shot-noise effects. We choose the redshift range to be $0.01 \leq z \leq 0.075$, for which the selection function for the total sample is $e^{0.14}$. The numbers of galaxies used to determine $\phi^*$ are given in Table 1 above. In Table 2, we give jackknife errors for $\phi^*$. The normalization significantly varies depending on the cutoff of the redshift range, reflecting the presence of large-scale structure, such as a clump seen between $z = 0.07$ and $z = 0.08$ in Figure 2. The variation of the normalization obtained by varying the upper cutoff between 0.07 and 0.08 is comparable to the jackknife error we quoted. The normalizations (and errors) are then corrected for the sample incompleteness derived in Table 2 by comparing the spectroscopic sample with good-quality photometry and redshift determinations (row 4 in Table 1) with the photometric sample (row 1 in Table 1). A small difference in the areas covered by the photometric and spectroscopic surveys is also taken into account. Furthermore, an extra correction factor of $1875 + 88 = 1.05$ is multiplied in to correct for the incompleteness of the photometric catalog, as discussed in §2.

We can see following features in our luminosity functions:

1. The characteristic luminosity and the faint-end slope of the total sample are consistent with the parameters derived by Blanton et al. (2001) within 1–1.3 $\sigma$. The normalization, however, is significantly lower than that of Blanton et al., corresponding to 30% in the luminosity density. This can be ascribed to the local deficit of galaxies in the northern...
equatorial stripe seen for $r^* < 16$ mag and is due to large-scale structure, as discussed in Yasuda et al. (2001). We confirmed that the normalization rapidly approaches that of Blanton et al. when we take a fainter limiting magnitude; with $r^* < 16.5$, the luminosity density agrees with that of Blanton et al. to within 10%.

2. The characteristic luminosity of early-type galaxies is brighter than that of late-type galaxies by about 0.45 mag. This is consistent with the “universal characteristic luminosity” known for the $B$ band (Tammann, Yahil, & Sandage 1979), because we expect the $B - r^*$ color to differ by 0.4 mag between E and Sb (Fukugita et al. 1995). This implies that the universal characteristic luminosity in the $B$ band is an accidental effect.

3. The shape of the luminosity function of early-type galaxies is not much different from that of late-type galaxies, although some trend is seen in that the number of early-type galaxies slightly declines ($\alpha \approx -1$) toward the faint end. This conclusion agrees with that of Marzke et al. (1994) for the $B$ band, and Kochanek et al. (2001) for the $K$ band, but does not agree with Loveday et al. (1992), which shows an appreciable decline toward the faint end (see Zucca, Pozzetti, & Zamorani 1994, who ascribe Loveday et al.’s result to sample incompleteness). In particular, we do not see a sharp decline of the luminosity function, as inferred by Binggeli et al. (1988) and Bernardi et al. (2003b). The latter authors fitted the luminosity function of early-type galaxies selected with photometric and spectroscopic parameters (Bernardi et al. 2003a) to a Gaussian function with a peak at $M_r = -20.38$ mag ($h = 1$); their data go beyond the peak only slightly, and the turnover is not conclusive. Our luminosity function, which goes down to $-18.75$ mag, does not show any turnover to this magnitude.

4. The luminosity function of late-type spirals (Sbc–Sd) does not exhibit an increase ($\alpha \gtrsim -1$) toward the faint end. Our late-type spiral galaxy sample shows an even faster decline compared with that of early-type spiral galaxies. We find that the luminosity function derived from $I_{\text{max}}$ shows a somewhat faster increase ($\alpha = -1.16$) compared with those for other types, but this trend is not visible with the MDLF from the ML and SWML methods. We ascribe this larger $\alpha$ from the $I_{\text{max}}$ method to a local effect of the galaxy distribution, as we mentioned above. In any case, the steepening of the faint-end slope does not occur up to the Im type. This might appear to contrast with the conventional belief that late-type galaxies have a steep slope. This is due to our exclusion of very late galaxies ($T > 5$) and is consistent with the result of Marzke et al. (1994), who found that only the Im luminosity function shows a steep faint-end slope.

5. The Im type luminosity function shows a steep faint-end slope, $\alpha \approx -1.9$, consistent with Marzke et al. (1994).

It may be worth commenting that the absolute magnitude distributions of early- and late-type spiral galaxies shown in Figure 3 appear to indicate a steeper faint-end slope for the latter. This is in fact what we obtained when using the $I_{\text{max}}$ method. This reflects the effect seen in Figure 2, that the morphological composition appears to change with redshift (i.e., the frequency of late-type spirals is high in the nearby, $z < 0.05$, sample). This effect disappears when we use the likelihood method to calculate the luminosity function under the assumption that it is universal.

For practical uses of the MDLF presented here, the normalization should be multiplied by a factor of 1.29 to correct for the local deficit of galaxies in the northern equatorial stripe at brighter magnitudes.
Shimasaku et al. (2001) report that this C-parameter shows the strongest correlation with visually classified morphology among simple photometrically defined parameters (see also Doi, Fukugita, & Okamura 1993; Abraham et al. 1994; Blanton et al. 2001; Strateva et al. 2001; Bernardi et al. 2003a). We thus separate morphologies into early and late types according to \( C < 0.35 \) and \( C > 0.35 \), which corresponds to a division at S0/a. The early-type galaxy sample (706 galaxies) thus defined shows an 82% completeness and is contaminated by late-type galaxies by 18% when we take the visually classified sample as the reference. The late-type sample (713 galaxies) also shows an 82% completeness and an 18% contamination from the opposite sample. This choice of \( C \) minimizes the contamination of the opposite morphologies either way. The analysis is similar to that presented by Blanton et al. (2001), with the difference that they used \( C = 0.43 \) (which corresponds to Sb for bright galaxies) to divide the early- and late-type galaxy samples.

Figure 6 shows the MDLF separated according to this C-index. The parameters of the Schechter function from the ML analysis are given in Table 2 above. The use of a different division, at \( C = 0.34 \), which corresponds roughly to S0 galaxies, changes the MDLF only slightly. The features of the luminosity functions are similar to those derived from the visually classified sample. The MDLF for early-type galaxies shows a characteristic luminosity brighter than that for late types and has a slightly declining faint-end shape, while late-type galaxies show a flat faint end. No sharp decline of the luminosity function is visible at least 2 mag fainter than the peak of the visually classified sample. The late-type galaxies declines somewhat at the faint end but does not exhibit a sharp decline, and this is not due to an increasing mixture of dwarf galaxies, at least in the magnitude range we are concerned with. The conclusion is unchanged if we use the concentration index as a classifier of early-type galaxies. This indicates that there are many intrinsically faint elliptical galaxies, whose luminosities are fainter than those of bulges in spiral galaxies. The existence of numerous early-type galaxies with hard cores at faint luminosities indicates that morphology is unlikely to be a bulge luminosity sequence as advocated by Dressler & Sandage (1983) and Meisels & Ostriker (1984). Our conclusion also justifies calculation of the strong gravitational lensing frequency of quasars using the standard Schechter function without introducing a cutoff in the luminosity function, which would affect the frequency of subarcsecond lensing.

5. CONCLUSIONS

Our sample is small and we may not be able to extract quantitatively robust parameters, yet we have obtained a number of useful conclusions. The most important feature of our analysis is that we have used a homogeneous photometric catalog with sharply defined selection criteria and a homogeneously morphologically classified sample based on the Hubble morphology of galaxies, rather than a sample classified by indicators using spectroscopic features or colors, which are sensitive to small-scale star formation activity in the present or the recent past.

The first conclusion we have obtained is that the shape of the MDLF does not depend too strongly on Hubble type. The characteristic luminosity of elliptical and S0 galaxies is brighter than that of spiral galaxies in the \( r^* \) band. The amount of the difference in brightness is consistent with a universal characteristic luminosity in the \( B \) band, which was found by Tamman et al. (1979). The MDLF of early-type galaxies declines somewhat at the faint end but does not exhibit a sharp decline, and this is not due to an increasing mixture of dwarf galaxies, at least in the magnitude range we are concerned with. The conclusion is unchanged if we use the concentration index as a classifier of early-type galaxies. This indicates that there are many intrinsically faint elliptical galaxies, whose luminosities are fainter than those of bulges in spiral galaxies. The existence of numerous early-type galaxies with hard cores at faint luminosities indicates that morphology is unlikely to be a bulge luminosity sequence as advocated by Dressler & Sandage (1983) and Meisels & Ostriker (1984). Our conclusion also justifies calculation of the strong gravitational lensing frequency of quasars using the standard Schechter function without introducing a cutoff in the luminosity function, which would affect the frequency of subarcsecond lensing.
REFERENCES

Abraham, R. G., Valdes, F., Yee, H. K. C., & van den Bergh, S. 1994, ApJ, 432, 75
Bernardi et al. 2003a, AJ, 125, 1817
———. 2003b, AJ, 125, 1849
Binggeli, B., Sandage, A., & Tammann, G. A. 1988, ARA&A, 26, 509
Blanton, M., et al. 2001, AJ, 121, 2358
Bromley, B. C., Press, W. H., Lin, H., & Kirshner, R. P. 1998, ApJ, 505, 25
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J.,
Paturel, G., & Fouqué, P. 1991, Third Reference Catalogue of Bright
Galaxies (New York: Springer)
Doi, M., Fukugita, M., & Okamura, S. 1993, MNRAS, 264, 832
Dressler, A., & Sandage, A. 1983, ApJ, 265, 664
Efstathiou, G., Ellis, R. S., & Peterson, B. A. 1988, MNRAS, 232, 431
Folkes, S., et al. 1999, MNRAS, 308, 459
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., &
Schneider, D. P. 1996, AJ, 111, 1748
Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, PASP, 107, 945
Fukugita, M., & Turner, E. L. 1991, MNRAS, 253, 99
Gunn, J. E., et al. 1998, AJ, 116, 3040
Hogg, D. W., Finkbeiner, D. P., Schlegel, D. J., & Gunn, J. E. 2001, AJ,
122, 2129
Kochanek, C. S., et al. 2001, ApJ, 560, 566
Kormendy, J. 1987, in Nearly Normal Galaxies, ed. S. M. Faber (New
York: Springer), 163
Loveday, J., Peterson, B. A., Efstathiou, G., & Maddox, S. J. 1992, ApJ,
390, 338
Marzke, R. O., da Costa, L. N., Pellegrini, P. S., Willmer, C. N. A., &
Geller, M. J. 1998, ApJ, 503, 617
Marzke, R. O., Geller, M. J., Huchra, J. P. & Corwin, H. G., Jr. 1994, AJ,
108, 427
Mei, & Ostriker, J. P. 1984, AJ, 89, 1451
Pier, J. R., Munn, J. A., Hindsley, R. B., Hennessy, G. S., Kent, S. M.,
Lupton, R. H., & Ivezić, Ž. 2003, AJ, 125, 1559
Sandage, A. 1961, The Hubble Atlas of Galaxies (Carnegie Inst. Washing-
ton Publ. 618) (Washington: Carnegie Inst.)
Sandage, A., Tammann, G. A., & Yahil, A. 1979, ApJ, 232, 352
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Shimasaku, K., et al. 2001, AJ, 122, 1238
Smith, J. A., et al. 2002, AJ, 123, 2121
Stoughton, C., et al. 2002, AJ, 123, 485 (erratum 123, 3487)
Strateva, I., et al. 2001, AJ, 122, 1861
Strauss, M. A., et al. 2002, AJ, 124, 1810
Tammann, G. A., Yahil, A., & Sandage, A. 1979, ApJ, 234, 775
Yasuda, N., et al. 2001, AJ, 122, 1104
York, D. G., et al. 2000, AJ, 120, 1579
Zucca, E., Pozzetti, L., & Zamorani, G. 1994, MNRAS, 269, 953