THE LUMINOSITY FUNCTION OF FIELD GALAXIES IN THE CNOC1 REDSHIFT SURVEY

H. Lin, H. K. C. Yee, R. G. Carlberg, and E. Ellingson

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ABSTRACT

We have computed the luminosity function for a sample of 389 field galaxies from the Canadian Network for Observational Cosmology cluster redshift survey (CNOC1) over the redshift range \( z = 0.2 - 0.6 \). We find Schechter parameters \( M^* = 5 \log h = -20.8 \pm 0.4 \) and \( \alpha = -1.3 \pm 0.2 \) in rest-frame Gunn \( r \), and \( M^*_B = 5 \log h = -19.6 \pm 0.3 \) and \( \alpha = -0.9 \pm 0.2 \) in rest-frame \( B_B \). We have also split our sample at the color of a redshifted but nonevolving Sbc galaxy and find distinctly different luminosity functions for red and blue galaxies. Red galaxies have a shallow slope \( \alpha \approx -0.4 \) and dominate the bright end of the luminosity function, while blue galaxies have a steep \( \alpha \approx -1.4 \) and prevail at the faint end. Comparisons of the CNOC1 results to analogous intermediate-redshift luminosity functions from the Canada-France (CFRS) and Autofib redshift surveys show broad agreement among these independent samples, but there are also significant differences which will require larger samples to resolve. Also, in CNOC1 the red galaxy luminosity density stays about the same over the range \( z = 0.2 - 0.6 \), while the blue galaxy luminosity density increases steadily with redshift. These results are consistent with the trend of the luminosity density versus redshift relations seen in the CFRS, although the normalizations of the luminosity densities appear to differ for blue galaxies. Comparison to the local luminosity function from the Las Campanas redshift survey (LCRS) shows that the luminosity density at \( z \approx 0.1 \) is only about half that seen at \( z \approx 0.4 \). A change in the luminosity function shape, particularly at the faint end, appears to be required to match the CNOC1 and LCRS luminosity functions, if galaxy evolution is the sole cause of the differences seen. However, it should be noted that the specific details of the construction of different surveys may complicate the comparison of results and so may need to be considered carefully.

Subject headings: galaxies: evolution — galaxies: luminosity function, mass function — galaxies: photometry — surveys

1. INTRODUCTION

The luminosity function of galaxies is a simple but fundamentally important quantity in the study of galaxy populations and their evolution. The luminosity function is of particular relevance to the problem of the excess counts of faint blue galaxies (e.g., Koo & Kron 1992; Koo 1996) and will provide important constraints toward the resolution of this question. In particular, accurate determinations of the luminosity function at both low and high redshifts are crucial. Large wide-angle redshift surveys are providing precise measurements of the luminosity function in the local \( z \approx 0 \) universe (e.g., Lin et al. 1996a; Marzke et al. 1994; Loveday et al. 1992), a necessary baseline on which to anchor models of galaxy evolution back to higher redshifts. Also, recent smaller but deeper redshift surveys have provided direct measurements of the luminosity function to redshifts \( z \approx 1 \) (e.g., Lilly et al. 1995; Ellis et al. 1996; Cowie et al. 1996; Glazebrook et al. 1995) and have revealed clear evidence for the evolution of the luminosity function with look-back time. Moreover, that evolution depends strongly on galaxy type, such that the luminosity density of blue, star-forming galaxies appears to have increased substantially by \( z \approx 0.5 \), whereas that of red, more quiescent galaxies appears to have changed relatively little.

In this paper we present the luminosity function for a sample of field galaxies obtained as part of the Canadian Network for Observational Cosmology cluster redshift survey (CNOC1). Although the CNOC1 survey was optimized for obtaining cluster galaxy redshifts, a concurrent sample of field galaxies was an important and necessary component needed in order to accomplish the main survey goal of an accurate measurement of \( \Omega \) from cluster dynamics (Carlberg et al. 1996). The 389 galaxies in the CNOC1 field sample considered in this paper span the redshift range \( z = 0.2 - 0.6 \), and our sample size is comparable to that of other surveys at these intermediate redshifts. Moreover, available color information allows us to subdivide our sample by galaxy type. The aim of this paper is to compute the luminosity function for the CNOC1 field galaxies and to compare our results to those from other intermediate-redshift surveys. We describe the CNOC1 data sample in § 2 and detail our methods in § 3. Our luminosity function results are then presented and discussed in § 4. We summarize our conclusions in § 5.

2. THE CNOC1 SURVEY DATA

The CNOC1 cluster redshift survey contains about 2600 velocities of cluster and field galaxies, observed in the fields of 16 high X-ray luminosity clusters spanning the redshift range \( z \approx 0.2 - 0.6 \). Photometric and spectroscopic observations were obtained using the multiobject spectrograph (MOS) at the Canada-France-Hawaii Telescope (CFHT) during 24 nights in 1993 and 1994. A detailed description of
the observational and data reduction techniques is given in Yee, Ellingson, & Carlberg (1996, hereafter YEC); here we briefly describe some relevant details.

The CNOC1 field sample used in this paper is defined to lie within the redshift limits $0.2 < z < 0.6$, and outside the individual CNOC1 cluster redshift limits given in Table 1 of Carlberg et al. (1996). In addition, further redshift limits are introduced by the use of four band-limiting filters, designed to optimize galaxy spectroscopy for clusters in different redshift ranges (YEC). For each filter, we set the low-redshift limit where $[\text{O} \text{I}] \lambda 3727$ would be 50 Å from the filter’s blue end, and we set the high-redshift limit where the G band would be 150 Å from the filter’s red end. (Note our high-redshift filter limits are more conservative than the corresponding limits given in YEC, which were based on detectability of Ca H + K. The addition of the G band here and the resulting more stringent limits should minimize the effect of any possible incompleteness at the high-$z$ ends of the filters, which we are still investigating.)

Selection of objects for spectroscopy was based on Gunn $r$ magnitudes (Thuan & Gunn 1976). In order to optimize the number of cluster redshifts, the fraction of galaxies spectroscopically observed was designed to decline with apparent magnitude. Thus, a magnitude selection weight $w_m$ (where $1/w_m$ is the fraction of objects with redshifts at a given apparent magnitude; see YEC) is assigned to each galaxy to properly weight its contribution in any statistical analyses (see below). In this paper we limit the sample to apparent magnitudes for which $w_m \leq 5$. Gunn $g$ magnitudes are also derived for each galaxy, and we further use a color selection weight $w_c(g - r)$ (Ellingson et al. 1996) to remove any residual color-dependent spectroscopic sampling effects not accounted for by the main magnitude selection weight. However, our results are little changed by inclusion of $w_c$.

We use the observed $g-r$ colors and interpolation among model galaxy spectral energy distributions (Coleman et al. 1980) to derive rest-frame colors and appropriate $k$-corrections for determination of absolute magnitudes $M_i$ in both the Gunn $r$ and $B_{485}$ (Oke 1972) systems. (For this purpose, we also need the transformations $r_{485} = r - 0.21$ and $g_{485} = g + 0.05$ given by Fukugita, Shimasaku, & Ichikawa 1995.) Throughout this paper we adopt a deceleration parameter $q_0 = 0.5$ and a Hubble constant $H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$; we use $h = 1$ if not otherwise indicated.

Finally, we limit the absolute magnitude range to $-22.0 < M_r < -17.5$ or $-21.5 < M_{g_{485}} < -17.0$, outside of which we have few observed galaxies. The final field sample consists of 389 galaxies. Table 1 summarizes the numbers, redshift limits, and apparent magnitude limits of our data sample.

| Filter | $N^a$ | Redshift Limits | Apparent Magnitude Limits$^a$ |
|--------|------|----------------|-------------------------------|
| Z2...... | 99  | 0.20–0.27       | 18.0 – 20.5                 |
| Z3...... | 45  | 0.27–0.38       | 19.0 – 21.5                 |
| Z4...... | 217 | 0.21–0.43       | 19.0 – 21.7                 |
| Z5...... | 27  | 0.45–0.60       | 20.0 – 22.0                 |

$^a$ Names of band limiting filters used for spectroscopy; see text and YEC for further details.

$^b$ The samples are further restricted to the Gunn $r$ absolute magnitude range $-22.0 < M_r < -17.5 \log h < -17.5$. The numbers remain the same for the alternative restriction $-21.5 < M_{g_{485}} < -17.0$, except that there is one additional galaxy in the Z4 sample.

$^c$ Gunn $r$ magnitudes.

$^d$ The value given in YEC was 0.27 and was based only on detectability of $[\text{O} \text{I}] \lambda 3727$. The present value is extended down to 0.21 based on the added detectability of $[\text{O} \text{I}] \lambda 3507, 4959$ at those low redshifts where $[\text{O} \text{I}] \lambda 3727$ would disappear off the blue end of a spectrum. Experience has shown that in the CNOC1 sample the $[\text{O} \text{I}]$ and $[\text{O} \text{II}]$ features are always detected simultaneously whenever they are all potentially visible.

3. METHODS

We compute the luminosity function using two related methods which are unbiased by density inhomogeneities in the galaxy distribution. These are the parametric maximum-likelihood method of Sandage, Tammann, & Yahil (1979, hereafter STY) and the nonparametric stepwise maximum-likelihood (SWML) method of Efstathiou, Ellis, & Peterson (1988, hereafter EEP). We briefly describe these methods below. Fuller descriptions may be found in the STY and EEP papers, as well as in Lin et al. (1996a).

Consider a galaxy $i$ observed at redshift $z_i$ in a flux-limited redshift survey. Let $m_{\min,i}$ and $m_{\max,i}$ denote the apparent magnitude limits of the field in which galaxy $i$ is located, and let us also impose absolute magnitude limits $M_1 < M < M_2$ on the sample. Let $\phi(M)$ be the differential galaxy luminosity function which we want to determine. Then the probability that galaxy $i$ has absolute magnitude $M_i$ is given by

$$p_i = p(M | z_i) \propto \phi(M_i) \int_{m_{\min,i}}^{m_{\max,i}} \phi(M)dM , \quad (1)$$

where $M_{\min}(z_i)$ and $M_{\max}(z_i)$ denote the absolute magnitude limits at $z_i$, corresponding to the given apparent magnitude limits. We can then form a likelihood function, $\mathcal{L}$, for having a survey of $N$ galaxies with respective absolute magnitudes $M_i$ by multiplying the individual probabilities $p_i$ together, obtaining

$$\ln \mathcal{L} = \sum_{i=1}^{N} \left\{ \ln \phi(M_i) - \ln \int_{m_{\min,i}}^{m_{\max,i}} \phi(M)dM \right\} W_i + \text{constant} . \quad (2)$$

Here the weight $W_i$ is a modification needed for the CNOC1 survey in order to account for the apparent magnitude and color selection effects described in § 2: $W_i = w_m w_c W_{k,i}$ (see Zucca et al. 1994).

In the STY method one assumes a parametric model for $\phi(M)$, and the parameters describing $\phi(M)$ are determined by maximizing the likelihood $\mathcal{L}$, or equivalently $\ln \mathcal{L}$, with respect to those parameters. In our case we take as our model for $\phi(M)$ the Schechter function (Schechter 1976)

$$\phi(M) = (0.4 \ln 10) \phi^* \left[ 10^{0.4(M^* - M)} \right]^{1+z} \exp \left[ -10^{0.4(M^* - M)} \right] , \quad (3)$$

and use the STY method to find the characteristic magnitude $M^*$ and the faint-end slope $z$. We emphasize that in the STY method, the determination of $M^*$ and $z$ are unbiased by the presence of galaxy density fluctuations in the survey, unlike the case for traditional least-squares luminosity function estimators (e.g., Felten 1977). On the other hand, the normalization $\phi^*$ drops out in equation (1) and has to be determined separately as described below. Error ellipses in the $M^*-z$ plane may be drawn by finding the contour corre-
sponding to
\[
\ln \mathcal{L} = \ln \mathcal{L}_{\text{max}} - \frac{1}{2} \Delta \chi^2 ,
\]
where \( \Delta \chi^2 \) is the change in \( \chi^2 \) appropriate for the desired confidence level and for a \( \chi^2 \) distribution with 2 degrees of freedom (e.g., \( \Delta \chi^2 = 6.17 \) at 2 \( \sigma \) confidence).

Alternatively, one does not have to assume a particular functional form for \( \phi(M) \). Rather, in the EEP stepwise maximum likelihood method (SWML), the luminosity function is taken to be a series of \( N_p \) steps, each of width \( \Delta M \) in absolute magnitude:
\[
\phi(M) = \phi_k, \quad M_k - \Delta M/2 < M < M_k + \Delta M/2 , \quad k = 1, \ldots, N_p. \tag{5}
\]
Here the likelihood is maximized with respect to the \( \phi_k \), which are solved for via an iterative procedure. Also, we can estimate the variances of the \( \phi_k \) and their errors.

To calculate the normalization \( \phi^* \) of the Schechter function (eq. [3]), as well as the mean galaxy number density \( \bar{\rho} \), we do the following. For galaxies \( i \) with redshift limits \( z_1 < z_i < z_2 \) and absolute magnitude limits \( M_1 < M_i < M_2 \), we estimate \( \bar{\rho} \) by
\[
\bar{\rho} = \frac{\sum_i W_i / S(z_i)}{V}, \tag{6}
\]
where \( V \) is the appropriate (comoving) volume and \( S(z) \) is the selection function defined by
\[
S(z) = \int_{z_{\text{max}}(M, M_1)}^{z} \phi(M) dM . \tag{7}
\]
The Schechter function normalization \( \phi^* \) is then just
\[
\phi^* = \frac{\bar{\rho}}{\int_{M_{\text{min}}(M_1, M_1)}^{M_{\text{max}}(M, M_1)} \phi(M) dM} , \tag{8}
\]
where \( \phi' \) is the Schechter function with \( \phi^* \) set to one. We use bootstrap resampling (e.g., Barrow, Bhavsar, & Sonoda 1984) to estimate the errors on \( \bar{\rho} \) and \( \phi^* \) contributed by uncertainties from fitting \( M^* \) and \( \alpha \), and from sampling and weighting fluctuations. This method does not include errors arising from galaxy density fluctuations, which we instead estimate using an appropriate integral over the galaxy clustering power spectrum \( P(k) \):
\[
\left( \frac{\delta \bar{\rho}}{\bar{\rho}} \right)^2 = \frac{1}{(2\pi)^3} \int d^3 k P(k) | W(k) |^2 . \tag{9}
\]
Here \( V \) denotes the volume of the particular sample under consideration, and \( W(k) \) is the window function for that volume, defined by
\[
W(k) = \frac{1}{V} \int d^3 r e^{i k \cdot r} . \tag{10}
\]
(That is, in \( V \) we explicitly account for the “pencil-beam” geometry of the CNOC1 fields.) For \( P(k) \) we adopt the local result derived from a 19000-galaxy sample drawn from the Las Campanas redshift survey (LCRS; Lin et al. 1996b), but multiplied by \( 1/(1+z)^2 \) to account for linear evolution (e.g., Peebles 1993, pp. 528–529) at the higher redshifts sampled in CNOC1. The final errors on \( \phi^* \) and \( \bar{\rho} \) consist of the quadrature sum of the bootstrap resampling and density fluctuation errors; it turns out for our sample that these two sources of error make roughly equal contributions. We will also calculate luminosity densities \( \rho_L \) for our galaxies, using
\[
\rho_L = \frac{\sum_i W_i 10^{-0.4 M_i / S_L(z_i)}}{V}, \tag{11}
\]
where
\[
S_L(z) = \int_{M_{\text{min}}}^{M_{\text{max}}} 10^{-0.4 M} \phi(M) dM . \tag{12}
\]
that is, we sum over the luminosities of our observed galaxies but weighted by the factor \( S_L(z) \), which uses the luminosity function \( \phi \) to extrapolate for the luminosity of unobserved galaxies lying outside the accessible survey flux limits. Note we use a finite \( M_{\text{faint}} \) (\( -17 + 5 \log h \) for both \( r \) and \( B_{48} \) bands) instead of \( +\infty \) to prevent the denominator of \( S_L(z) \) from blowing up when \( x < -2 \), as sometimes occurs during bootstrap resamplings of our blue galaxy subsample (§ 4). Also, note that our survey apparent flux limits prevent us from measuring the luminosity function for galaxies fainter than our chosen \( M_{\text{faint}} \) (see end of § 2). We estimate errors on \( \rho_L \) with the same method used on \( \phi^* \) and \( \bar{\rho} \).

We have thus far neglected the effects of photometric errors. This is actually a reasonable simplification, as 99\% of our sample galaxies have estimated errors of less than 0.1 mag. Assuming a Gaussian magnitude error distribution with dispersion \( \sigma = 0.1 \) mag, we can correct for the effects of photometric errors on the luminosity function using the method described in EEP § 3.5. We find that neglecting photometric errors only biases \( M^* \) and \( \alpha \) by at most \( \Delta M^* = -0.02 \) and \( \Delta \alpha = -0.01 \), much smaller than our 1 \( \sigma \) uncertainties (Table 2). We can thus safely neglect the effects of photometric errors in the rest of this paper.

Finally, note that for galaxies within our adopted filter redshift limits, the magnitude selection weights \( w_{\text{m}} \) will be slight overestimates, for the following reason. Recall that \( w_{\text{m}} \) is basically the ratio (at a given apparent magnitude \( m \) of the total number of galaxies to the number of galaxies with redshifts. However, since we include galaxies both inside and outside the filter redshift limits when computing this ratio, and since the redshift success rate will be lower for galaxies outside the filter limits than for those inside, \( w_{\text{m}} \) will be overestimated for those galaxies inside the limits. The amount of overestimate can be approximately calculated once some simplifying assumptions are made. We adopt specific values for \( M^* \) and \( \alpha \) (those we find below in § 4; we further assume that the luminosity function does not change with redshift), and we take our redshift sampling rate to be some constant within a given set of filter redshift limits. It turns out that the effect is approximately independent of apparent magnitude, so that the luminosity function shape is not affected. The luminosity function normalization will, however, be too large by roughly 20 ± 10\% for our adopted filter limits, where the uncertainty represents the range of scatter observed for different apparent magnitudes and filters. We do not explicitly include this systematic correction in our luminosity function normalizations, as it is comparable to our random errors, as well as somewhat complicated to deal with exactly (e.g., we need to model the change of luminosity function with redshift, as well as iterate the luminosity function and “renormalization” calculations until convergence). However, we will need to keep
the approximate 20% correction in mind when comparing our results to those of other surveys, as we do below.

4. RESULTS

Our luminosity function fit results are given in Table 2, for both rest-frame Gunn $r$ and rest-frame $B_{AB}$. Figures 1 and 2 show the 2 $\sigma$ error ellipses in the $M^*$ and $\alpha$ parameters, and Figures 3 and 4 plot the actual luminosity functions $\phi(M)$. The results are shown for the full 389 galaxy sample, as well as for two subsamples of galaxies whose rest-frame colors are either redder (209 galaxies) or bluer (180 galaxies) than that of an Sbc galaxy (model of Coleman, Wu, & Weedman 1980). Overall, the full sample luminosity functions have Schechter parameters $M^* = -20.8$ and $\alpha = -1.3$ in Gunn $r$, and $M^* = -19.6$ and $\alpha = -0.9$ in $B_{AB}$. Note the clear distinction between the red and blue subsample luminosity functions shown in Figures 3 and 4: the red subsample has a shallow $\alpha = -0.4$ and dominates the galaxy population at the bright end ($M_r, M_{B,AB} \lesssim -19.5$), while the blue subsample has a much steeper $\alpha = -1.4$ to $-1.5$ and consequently dominates at the faint end ($M_r, M_{B,AB} \gtrsim -19.5$). The error ellipses for the red and blue subsamples are clearly separated for both Gunn $r$ and $B_{AB}$, as seen in Figures 1 and 2, respectively.

We next compare our results against those from the two other largest surveys with $B$-band luminosity functions available at comparable intermediate redshifts, specifically the Canada-France redshift survey (CFRS; Lilly et al. 1995) and the Autofib redshift survey (Ellis et al. 1996). We start

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**TABLE 2**

| Sample | $N$  | $M^* - 5 \log h^{\text{b}}$ | $\alpha^{\text{b}}$ | $\phi^{\text{c,e}}$ | $\rho_L^{d,e}$ |
|--------|-----|-----------------|--------------|-----------------|----------------|
| Gunn $r$: |
| All ... | 388 | $-20.80 \pm 0.40$ | $-1.25 \pm 0.19$ | $0.021 \pm 0.008$ | $4.3 \pm 0.5$ |
| Red ... | 209 | $-20.24 \pm 0.30$ | $-0.42 \pm 0.28$ | $0.024 \pm 0.005$ | $2.3 \pm 0.3$ |
| Blue ... | 179 | $-20.24 \pm 0.52$ | $-1.47 \pm 0.32$ | $0.013 \pm 0.009$ | $1.8 \pm 0.4$ |
| $B_{AB}$: |
| All ... | 389 | $-19.63 \pm 0.25$ | $-0.89 \pm 0.21$ | $0.042 \pm 0.010$ | $3.6 \pm 0.4$ |
| Red ... | 209 | $-19.46 \pm 0.30$ | $-0.38 \pm 0.29$ | $0.024 \pm 0.005$ | $1.8 \pm 0.3$ |
| Blue ... | 180 | $-19.85 \pm 0.50$ | $-1.44 \pm 0.32$ | $0.014 \pm 0.009$ | $2.0 \pm 0.4$ |

$^a$ Absolute magnitude restrictions $-22.0 < M_r - 5 \log h < -17.5$ for Gunn $r$, and $-21.5 < M_{B,AB} - 5 \log h < -17.0$ for $B_{AB}$, are applied in the definitions of the samples and the calculations of the luminosity function and associated parameters, except that $\rho_L$ is computed for $-\infty < M - 5 \log h < -17$.  
$^b$ Errors are 1 $\sigma$ one-parameter errors determined from the STY fits. See Figs. 1 and 2 for the full two-parameter $M^*-\alpha$ error ellipses.  
$^c$ Units are $h^3$ Mpc$^{-3}$ mag$^{-1}$. Errors are 1 $\sigma$ and are estimated as described in the text.  
$^d$ Units are $10^3 L_\odot$ h Mpc$^{-3}$. We take Gunn $r_\odot = 4.84$ and $B_{AB0} = 5.34$, as inferred from solar photometric data from Allen 1973, § 75, and photometric transformations from Kent 1985 and Fukugita et al. 1995. Errors are 1 $\sigma$.  
$^e$ Note that $\phi^*$ and $\rho_L$ should likely be reduced by about 20%, due to the systematic effect discussed at the end of § 3.

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**FIG. 1**—2 $\sigma$ error ellipses in $M^*$ and $\alpha$ for the $r$-band luminosity functions from the CNOC1 and Las Campanas redshift surveys.

**FIG. 2**—2 $\sigma$ error ellipses in $M^*$ and $\alpha$ for the $B$-band luminosity functions of the CNOC1 samples. Also shown are $M^*$ and $\alpha$ values for samples from the Canada-France (CFRS) and Autofib redshift surveys. Results for red and blue galaxy subsamples are shown only for CNOC1 and CFRS.
with the CFRS. In Figures 2 and 4 we plot the CFRS $B_{AB}$-band results for a sample of 208 galaxies in their $z = 0.2–0.5$ bin (their “best” estimates). The CFRS sample has also been divided into red and blue subsamples at the same Sbc color cut used in CNOC1, and we show the corresponding results as well. Note first from Figure 2 that the CFRS $M_*$ and $\alpha$ values are just outside the respective CNOC1 2 $\sigma$ error ellipses. Remembering that the corresponding CFRS error ellipses will be larger (the CFRS sample is about half the size of CNOC1), we find that the CNOC1 and CFRS $M_*$ and $\alpha$ values agree at better than the 2 $\sigma$ level for each of the all, red, and blue samples. However, when we plot the actual luminosity functions in Figure 4, we find that although the shapes (i.e., $\alpha$) of corresponding CNOC1 and CFRS luminosity functions agree fairly well, the CNOC1 results tend to show brighter $M_*$ values and higher normalizations, especially in the case of the blue subsample. Recall that the CNOC1 normalization is likely an upper bound and may have to be decreased by about 20%, which would help improve the match with CFRS. An additional decrease in the CNOC1 $M_*$ by 0.2 mag (cf. Figure 2) would be needed to bring the CNOC1 and CFRS full-sample luminosity functions into very close agreement.

We consider next some possible causes for the differences, though none of them are entirely satisfactory. Extinction, which has been neglected in our analysis, should only have a small effect (as our photometry was in the $r$-band) and would actually brighten our $M_*$ values. Large-scale structure may bias the CNOC1 normalization high, as our field samples are in the neighborhood of rich clusters. However, we find that our results are little changed even when we triple the adopted cluster redshift limits (from about $\pm 3000$ km s$^{-1}$ to $\pm 9000$ km s$^{-1}$ from the cluster centers) in order to reduce the effects from potential large-scale structure associated with the clusters. Moreover, one expects the discrepancies to be larger for red galaxies (as they are more common in dense environments), but the observed differences are actually larger for blue galaxies. Also, the choice of spectral energy distributions used here to calculate $k$-corrections and to make the red/blue cuts is the same as that in CFRS. We also verified that we could reproduce the CFRS luminosity function results using our code on their redshift catalog data. A final possibility is that there remains some unaccounted systematic offset of order 0.2 mag in the photometry zero points, arising from the relatively independent ways the photometry was obtained and reduced in the two surveys. In the end, the differences may simply reflect actual sampling fluctuations. It is nevertheless encouraging that the luminosity function shapes of corresponding CNOC1 and CFRS samples are quite similar. Also, even before the 20% correction to the CNOC1 normalization, the luminosity densities from the two surveys do not differ at more than the 2 $\sigma$ level (see also below). Overall the CNOC1 and CFRS results are roughly consistent, showing the same luminosity function shapes but with normalization and $M_*$ differences, both at about the 20% level. We note that the CNOC1 sample provides somewhat better luminosity function measurements in the range $z = 0.2–0.6$ because of its larger sample size. On the other hand, the full CFRS sample extends to $z \approx 1$ and provides a longer baseline for studying the evolution of red and blue galaxy luminosity functions, a point we return to below.

Next, in Figures 2 and 5 we compare our results against the $z = 0.15–0.35$ and $z = 0.35–0.75$ luminosity functions from the Autofib survey. (The Autofib survey results are in the $b_J$ system, which is close enough to $B_{AB}$ that we will not apply any zero-point corrections; cf. Fukugita, Shimasaku, & Ichikawa 1995. Also, there are no results for red and blue subsamples.) Here the agreement is worse than it was with CFRS. Both Autofib samples show steeper faint-end slopes than those of CNOC1 and CFRS. The $M_*$ and $\alpha$ values are discrepant at the 2–3 $\sigma$ level compared to CNOC1 (the corresponding error ellipse for the Autofib $z = 0.15–0.35$ sample is smaller than that of the CNOC1 all sample, while that for $z = 0.35–0.75$ is comparable in size to that of CNOC1; see Fig. 11 of Ellis et al. 1996). Examination of

![Figure 3](image1.png)

**Fig. 3.** The $r$-band luminosity function of CNOC1 samples. The lines are the STY fits, while the points are SWML solutions with 1 $\sigma$ errors. Also shown is the STY fit from the Las Campanas survey.

![Figure 4](image2.png)

**Fig. 4.** The $B_{AB}$-band luminosity functions of CNOC1 samples are compared to those of corresponding CFRS samples. The points show SWML solutions for the CNOC1 all sample.
shift cuts are applied, we are not able to rule out (or in) changes in $M^*$ of order 0.5 mag over $0.2 < z < 0.6$.

We will instead examine changes in the galaxy luminosity density $\rho_L$ as a function of $z$ and adopt the simple procedure of fixing $M^*$ and $x$ at the values given in Table 2 for all $z$. We plot the $B_{AB}$-band luminosity density $\rho_L$ versus $z$ in four redshift bins in Figure 5, for the all, red, and blue samples.

To facilitate comparison with other surveys, we have rescaled our $\rho_L$ results for $M_{\text{faint}} = -17 + 5 \log h$ to $M_{\text{faint}} = +\infty$; recall eq. [12].) The errors plotted are 1 $\sigma$ estimates as described in § 3, with roughly equal contributions from bootstrap resampling and density fluctuation uncertainties.

Figure 5 shows that the CNOC1, Auto$b$, and CFRS luminosity functions are only broadly consistent with each other, with Auto$b$ samples showing the steepest slopes and lowest normalizations. It is curious that the Auto$b$ results actually resemble that of our blue subsample well (though this is not to suggest that they are incomplete in red galaxies). Some of the same points raised above in discussing the CNOC1 and CFRS differences apply here as well. Also, though the Auto$b$ sample is the largest among the three surveys, there are some differences in their survey construction compared to CNOC1 and CFRS. Unlike CNOC1 or CFRS, the Auto$b$ sample is actually a combination of a number of disparate redshift surveys, carried out with different instruments and telescopes. Instead of CCD photometry, the Auto$b$ survey is based on photographic plate photometry. Also, the original photometry is in the $b_j$ band, rather than at longer wavelengths like $r$ (CNOC1) or $I$ (CFRS). Consequently the $k$-corrections needed to convert to rest-frame $B$ are largest for the Auto$b$ samples. Ellis et al. (1996) and references therein detail a careful treatment of these various issues. While we do not claim that any of these is the cause of the luminosity function differences, we do suggest that the details of the construction and selection of galaxy samples from one survey to another are complicated enough that they may systematically affect comparison of results among different samples. The less than ideal agreement shown in Figure 5 indicates that even larger samples, with well-defined selection criteria, are needed to make a definitive determination of the luminosity function at intermediate redshifts.

Now we proceed to examine the issue of galaxy evolution within the CNOC1 sample. We have divided the CNOC1 samples by redshift to look for changes in $M^*$ and $x$ as a function of $z$. We find there to be no significant changes in $M^*$ or $x$ with redshift, within the respective $2 \sigma$ error ellipses of the $z$-divided samples. This holds for the full sample, as well as for the red and blue galaxy subsamples. However, because the error ellipses do get quite large when the red-
If we apply the likely 20% normalization reduction for CNOC1 discussed before, the results agree better, as also shown in Figure 6. In any event, the CNOC1 trends are at least qualitatively consistent with those seen in the CFRS: strong evolution of the luminosity density of blue galaxies but little evolution of that of red galaxies. Moreover, Schade et al. (1996) have found that the surface brightness of disk galaxies in the CNOC1 survey increases with $z$ in a way consistent with the shape of the CFRS $p_L-z$ relation; our current results thus also corroborate the earlier CNOC1 findings. That the differences between CNOC1 and CFRS lie in the absolute normalizations rather than in the shapes suggests that within each survey, we are basically measuring the same galaxy luminosity density trends, but that there is some unaccounted systematic normalization or scaling difference, particularly for blue galaxies, which causes the disagreement when we compare across the two surveys.

We have also checked that our red/blue luminosity function and luminosity density evolution differences are robust to potential errors in assigning galaxies to the red and blue samples (e.g., a potential wavelength-dependent error in our model Sbc galaxy spectrum can lead to a redshift-dependent type assignment error). We do this check by more finely dividing our sample into three roughly equal parts by color. We find that the steep faint end of the blue luminosity function and the increase of the blue luminosity density at higher redshift both result primarily from galaxies in the bluest third of our sample, rather than from blue galaxies near the Sbc dividing line. In the latter case our results would have been more sensitive to potential type-assignment errors, but as the former case is the actual situation, our conclusions regarding the red/blue differences should not be affected.

Finally, we compare our r-band results against those from the local sample of 18,678 Las Campanas redshift survey (LCRS) galaxies, the largest galaxy sample for which the luminosity function has been computed (Lin et al. 1996a). The LCRS galaxies have an average redshift $z = 0.1$ and are also observed in the red. From Figures 1 and 3, we find that the local LCRS luminosity function is clearly different from the intermediate-redshift CNOC1 results. The CNOC1 results show a brighter $M^*$, a steeper faint-end slope $\alpha$, as well as a higher normalization compared to the LCRS. We note that if the differences result purely from galaxy evolution, that evolution needs to be luminosity dependent as well, as the differences become larger at the faint end of the luminosity function. In terms of luminosity densities, the LCRS has $p_L = (1.9 \pm 0.2) \times 10^8 L_\odot h^{-1}$ Mpc$^{-3}$, about half that of the CNOC1 sample. The increase in luminosity density at intermediate redshifts relative to the local value appears to be a robust conclusion, as the CNOC1 results are corroborated by independent samples like CFRS and Autofib (despite the differences among the intermediate-redshift samples). However, a careful consideration and account of systematic effects will be especially important for a definitive assessment of the causes of the differences. For example, different surface brightness limits of local versus deeper surveys (Ferguson & McGaugh 1995), or different photometry methods (different aperture sizes, limiting isophotes, etc.) can cause differences in the luminosity function that have nothing to do with actual galaxy evolution. Though beyond the scope of this paper, such a detailed modeling of both evolutionary and observational effects is planned for the ongoing CNOC2 redshift survey, a successor of CNOC1, which should eventually provide a much larger sample of several thousand intermediate-redshift field galaxies for study.

5. CONCLUSIONS

We have computed the rest-frame Gunn $r$ and $B_{AB}$ luminosity functions for a sample of 389 field galaxies from the CNOC1 redshift survey, over the redshift range $z = 0.2 - 0.6$. We find Schechter parameters $M^*_r = -5 \log h = -20.8 \pm 0.4$ and $\alpha = -1.3 \pm 0.2$ in Gunn $r$, and $M^*_{AB} = -5 \log h = -19.6 \pm 0.3$ and $\alpha = -0.9 \pm 0.2$ in $B_{AB}$. Samples of red and blue galaxies, cut at the rest-frame $g - r$ color of an Sbc galaxy, show distinctly different luminosity functions. Red galaxies have a shallow slope $\alpha \approx -0.4$ and dominate the bright end of the luminosity function, while blue galaxies have a steep $\alpha \approx -1.4$ and prevail at the faint end. Table 2 summarizes our results.

Comparisons of the CNOC1 results to independently determined intermediate-redshift luminosity functions show broad agreement with results from the CFRS and Autofib redshift surveys. However, there are questions about particular differences in the luminosity functions which will require larger samples to resolve. Calculation of the $B_{AB}$-band luminosity density shows that the CNOC1 red galaxy luminosity density is about the same from $z = 0.2 - 0.6$ but that the blue luminosity density over $z = 0.4 - 0.6$ is nearly 3 times that for $z = 0.2 - 0.4$. These trends are consistent with those derived from the CFRS (see Fig. 6), except for a normalization difference resulting primarily from blue galaxies, and are also consistent with the redshift evolution of disk galaxy surface brightness observed in CNOC1. Comparison to the local luminosity function from the Las Campanas redshift survey implies that the luminosity density at $z \approx 0.1$ is only about half that seen at $z \approx 0.4$. Also, luminosity-dependent evolution, increasing at the faint end, would seem to be required to match the CNOC1 and LCRS luminosity functions, if galaxy evolution is the sole cause of the differences seen.

However, an underlying caveat throughout our comparisons of CNOC1 results with those of other surveys is that the particular details of the construction of different surveys may have an important effect on how we interpret the results. Along these lines, we have pointed out some potential systematic causes of the differences among the various survey luminosity functions we considered, although we have not attempted a detailed investigation. It is probably fair to say that control of systematic effects within a single survey is simpler than across different surveys, and perhaps that is why the red/blue luminosity density trends appear to have the same shapes but different normalizations in CNOC1 and CFRS. In any event, the CNOC1 field sample is still relatively small, and a larger sample will definitely help confirm or reject some of the trends that we have seen in CNOC1, as well as help resolve the differences seen versus other surveys. In particular, the CNOC2 field redshift survey should provide us with an order of magnitude larger sample of several thousand objects to examine the luminosity and other properties of galaxies at intermediate redshifts. We thus anticipate a similar but more detailed analysis for the CNOC2 data in the near future, and a

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4 Specifically an isophotal, "hybrid" Kron-Cousins R-band (details in Tucker 1994 and Lin et al. 1996a), the zero point of which is within ±0.1–0.2 mag of the Gunn r system used for CNOC1.
thorough investigation of the evolution of galaxies from intermediate to low redshifts.

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