Results on Galaxy Evolution from the CNOC2 Field Galaxy Redshift Survey

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Abstract. The CNOC2 Field Galaxy Redshift Survey presently contains some 5000 galaxy redshifts, plus extensive $UBgRI$ photometry, and is the largest galaxy sample at moderate redshifts $0.1 < z < 0.6$. Here we present some *preliminary* results on the galaxy luminosity function (LF) and its redshift evolution, using a sample of $R < 21.5$ CNOC2 galaxies, subdivided into early, intermediate, and late types based on their $B - R$ colors relative to *non-evolving* galaxy models. We find a significant steepening in the faint-end slope α of the LF as one proceeds from early to late types. Also, for all galaxy types we find a rate of M^* evolution consistent with that from passively evolving galaxy models. Finally, late-type galaxies show positive density evolution with redshift, in contrast to negative or no density evolution for earlier types.

1. Introduction to the Survey

The determination of the clustering, luminosity, star formation and other properties of galaxies, and the measurement of the evolution of those properties with redshift, are fundamentally important goals of observational cosmology. The CNOC2 (Canadian Network for Observational Cosmology) Field Galaxy Redshift Survey is explicitly designed to study the evolution of galaxy clustering and luminosity properties over $0.1 < z < 0.6$, and currently constitutes the largest galaxy sample at these intermediate redshifts (see Yee et al. 1997 for more details). The survey has a total area of some 1.5 deg^2, in the form of 4 widely-separated patches on the sky, where each patch is an "L"-shape that spans about 1.5°. The spectroscopic observations are carried out at the Canada-France-Hawaii Telescope, using efficient MOS multi-slit spectroscopy of typically 100 objects at once. This is made possible with a band-limiting filter that re-

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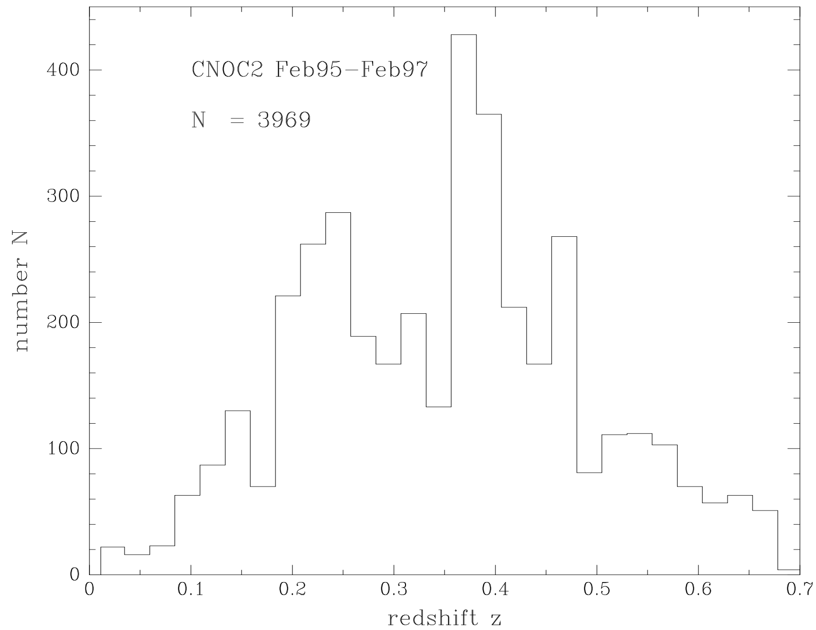

Figure 1. The present CNOC2 survey redshift histogram. Note that another 1000 redshifts have been obtained but are not yet reduced.

stricts the spectra to 4300-6300 Å, resulting in a redshift range $0.12 < z < 0.55$ with unbiased coverage of important galaxy absorption and emission features. Redshift errors are about 75 km s^{-1} in the rest frame. The survey also includes 5-color $UBgRI$ photometry for nearly all fields (plus K for some), with average 5σ limits at (Kron-Cousins) $R = 24.0$ and $B = 24.6$.

At present (11/97) the CNOC2 survey is 80% complete, with 3 of the 4 patches essentially done. The survey contains some 5000 redshifts, with nearly 4000 for galaxies brighter than the nominal $R = 21.5$ spectroscopic completeness limit, at which the cumulative redshift sampling rate is about 1 in 2. Figure 1 shows the redshift histogram for the survey, and Figure 2 plots observed $B - R$ color vs. redshift. In the present paper we discuss some *preliminary* results on the evolution of the galaxy luminosity function, using a subset of about 2000 $R < 21.5$ galaxies from the "0223" and "0920" patches, which are the 2 current patches with almost fully reduced redshift and 5-color data. We adopt $H_0 = 100\ h$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ throughout, as is typically done in the analysis of other redshift surveys at similar z.

2. The Luminosity Function

The luminosity function (LF) of galaxies is a fundamentally important quantity in the study of galaxy populations and their evolution. Accurate determinations of the LF at both low and high redshifts are crucial. Large wide-angle redshift surveys are providing precise measurements of the luminosity function in the local $z \sim 0$ universe (e.g. Loveday et al. 1992; Marzke et al. 1994b; Lin et al. 1996), and smaller but deeper surveys have begun to measure the LF up to

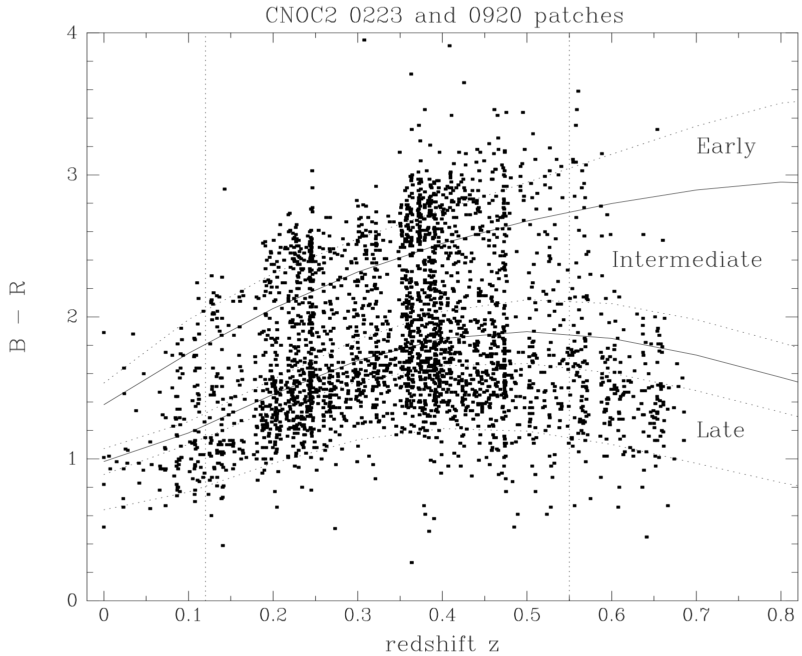

Figure 2. $B-R$ color vs. z for CNOC2 galaxies. Dotted lines show k-corrected $B-R$ from Coleman, Wu, & Weedman (1980) SED's, and solid lines show the interpolations used to subdivide CNOC2 galaxies. The vertical lines denote the redshift range $0.12 < z < 0.55$, within which there is unbiased coverage of spectral features important to redshift identification for all galaxy types.

redshifts $z \sim 1$ (e.g., Lilly et al. 1995; Ellis et al. 1996; Cowie et al. 1996; Lin et al. 1997), revealing clearly the rapid evolution of the LF of blue, star-forming galaxies, but relatively little change in the LF of red, more quiescent objects. Here we will examine the luminosity function and its evolution for galaxies of different types in the CNOC2 sample, and we will exploit the large CNOC2 sample size to derive improved constraints.

Figure 3 shows the B_{AB}-band luminosity function for a sample of 2075 galaxies, with $R < 21.5$ and $0.12 < z < 0.55$, from the CNOC2 0223 and 0920 patches. The LF is computed using standard inhomogeneity-independent maximum-likelihood techniques (e.g., Efstathiou, Ellis, & Peterson 1988). The CNOC2 LF appears to be well fit by a nearly-flat Schechter function ($\alpha = -0.8$), and it is also consistent with the $0.2 < z < 0.5$ LF from the Canada-France Redshift Survey (CFRS; Lilly et al. 1995), as seen in the comparison of 2σ M^*-α error ellipses in the Figure 3 inset. Note in particular the much smaller LF uncertainties of the CNOC2 sample, which contains about ten times as many galaxies as the CFRS over the same redshift range.

However, as has been observed in many previous galaxy samples, the luminosity function does appear to depend on various galaxy properties, such as rest-frame color, spectral type, or morphology (see e.g., Lilly et al. 1995; Lin et al. 1996, 1997; Heyl et al. 1997; Marzke et al. 1994a). To check the type dependence of the LF, we have also divided CNOC2 galaxies into early, inter-

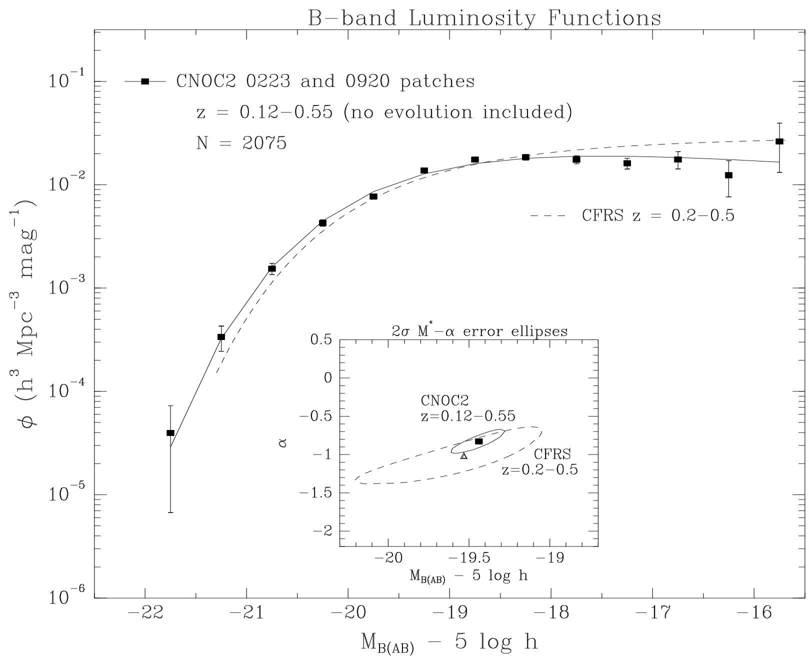

Figure 3. Comparison of the CNOC2 B_{AB}-band luminosity function with that from the much smaller CFRS sample.

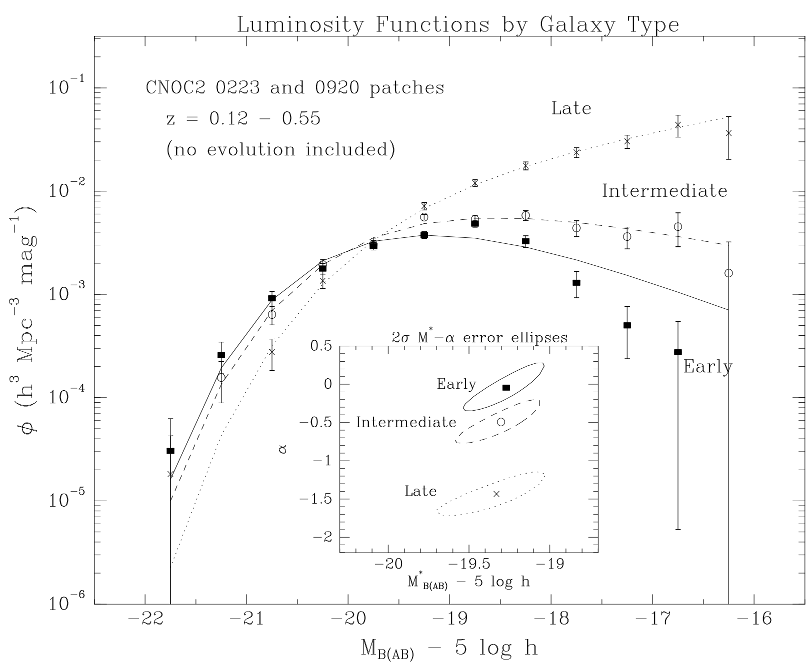

Figure 4. Comparison of B_{AB}-band luminosity functions for CNOC2 galaxies of different types, classified by observed $B-R$ color as shown in Figure 2.

mediate, and late types (more precisely red, intermediate, and blue), based on k-corrected $B - R$ colors computed from non-evolving Coleman, Wu, & Weedman (1980; CWW) spectral energy distributions (SED's; Figure 2). Figure 4 then clearly shows that the luminosity function depends on galaxy type, with a strong steepening of the faint-end slope α as one proceeds from red, early-type galaxies to blue, late-type ones. These type-dependent differences are also quite significant, as shown in the Figure 4 inset, and are also similar to those seen in previous smaller surveys at moderate redshifts, including the CFRS (Lilly et al. 1995) and Autofib (Ellis et al. 1996) samples.

3. Luminosity and Number Density Evolution

So far the LF's have been fit without regard to evolution, but we know from previous surveys that galaxies do evolve significantly over $z < 1$. As a simple but useful parameterization of luminosity and number density evolution, we adopt the following model:

$$\begin{aligned} \rho(z) &= \rho(0)10^{0.4Pz} \\ M^*(z) &= M^*(0) - Qz \\ \alpha(z) &= \alpha(0) \end{aligned} \tag{1}$$

where ρ is the galaxy number density, P quantifies the rate of number density evolution, and Q describes the rate of M^* or luminosity evolution. P and Q are essentially just the linear coefficents in an expansion in z of ρ and M^*, respectively. For simplicity, α is assumed not to evolve so that the LF shape does not change with redshift. We use maximum-likelihood techniques to derive best-fitting LF and evolution parameters, and Figure 5 shows the resulting 1σ P vs. Q error ellipses for the three CNOC2 galaxy types, which do indeed show different evolutionary trends. In particular, late-type galaxies show positive density evolution ($P > 0$ so ρ increases at higher z), early-type galaxies show negative density evolution ($P < 0$), and intermediate types show no density evolution. On the other hand, all three galaxy types show positive luminosity evolution, i.e. M^* is brighter in the past, and the derived values of $Q \approx 1 - 2$ are consistent with those expected from passively evolving galaxy models (e.g., Bruzual & Charlot 1993). (Note that using $q_0 = 0.1$ instead of $q_0 = 0.5$ will roughly decrease P by 0.8 and increase Q by 0.4.)

Also, in our parameterization, the luminosity density varies as $\rho_L(z) = \rho_L(0)10^{0.4(P+Q)z}$, so $P + Q$ characterizes the rate of evolution of the luminosity density. Figure 6 plots ρ_L vs. z for the three galaxy types and shows the rapid rise in the luminosity density of late-type galaxies relative to that of early- and intermediate-type galaxies, again consistent with similar trends seen in previous smaller surveys (e.g., Lilly et al. 1996; Lin et al. 1997). Finally, Figure 7 compares the observed CNOC2 galaxy number counts with those predicted by the LF and evolution parameters fit from the spectroscopic data *alone*. The observed and LF-predicted counts are in good agreement for all 5 CNOC2 bands, showing that our simple 3-population evolution model is a reasonable description, and that there are no conspicuous unaccounted spectroscopic selection effects. Note also from the R counts that our LF evolution model remains valid beyond the

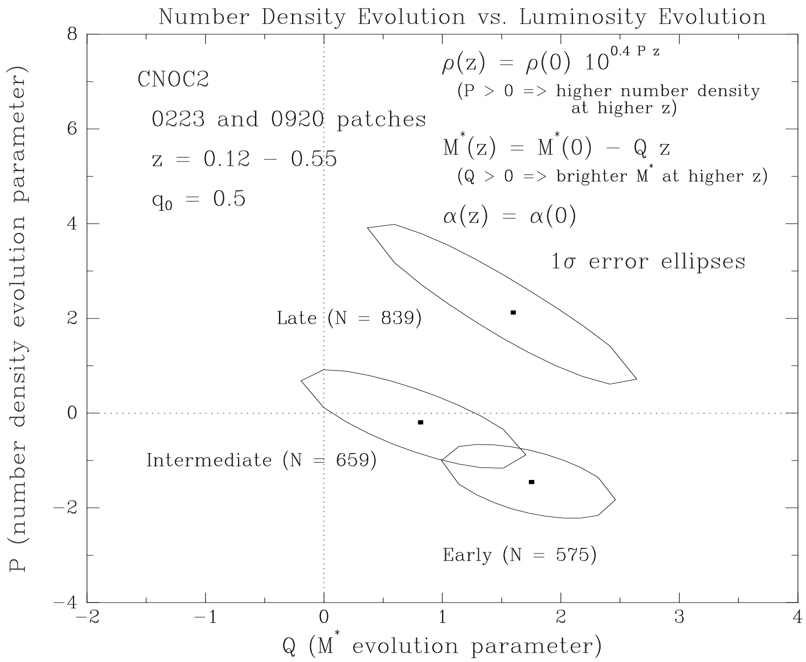

Figure 5. 1σ error ellipses in P (the number density evolution parameter) vs. Q (the M^* evolution parameter), for different CNOC2 galaxy types.

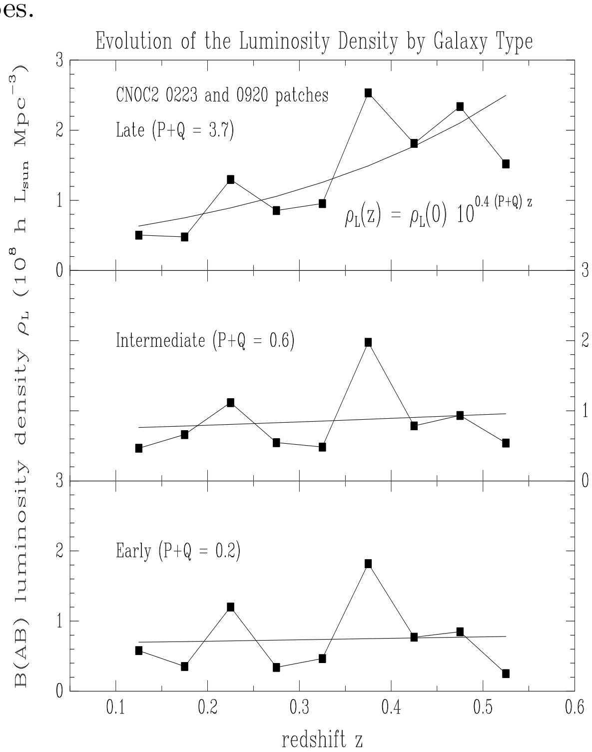

Figure 6. The redshift evolution of the B_{AB}-band luminosity density ρ_L for different CNOC2 galaxy types.

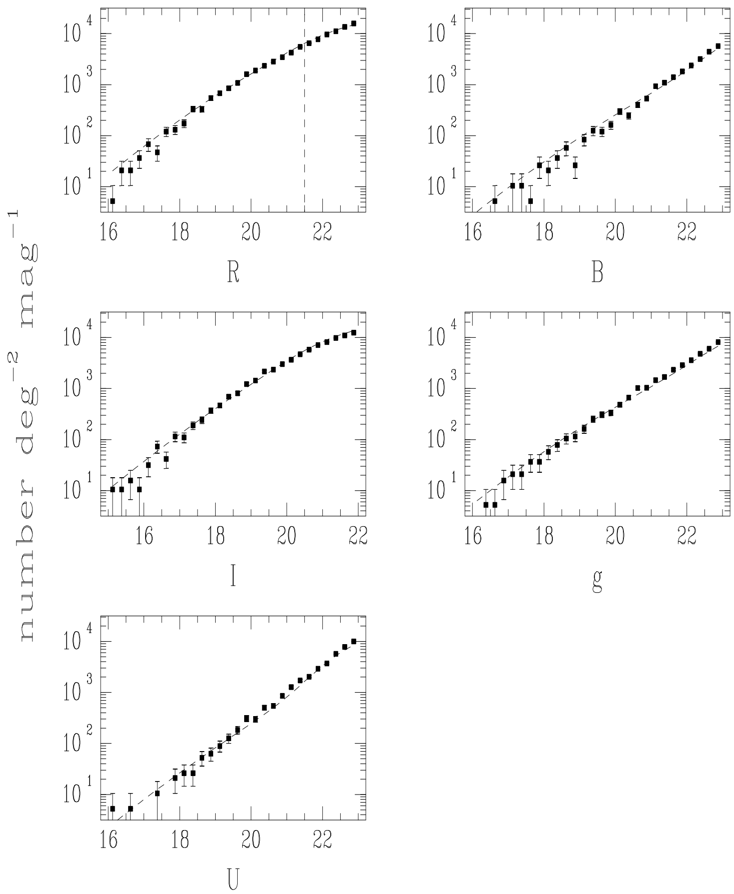

Figure 7. Comparison of observed CNOC2 galaxy counts (points), in the R, B, I, g, and U bands, with those computed from the LF evolution model fit to the spectroscopic sample (lines). Note that the spectroscopic sample used to derive the LF evolution parameters is limited to $R < 21.5$, as indicated by the vertical line in the R panel.

adopted $R = 21.5$ limit of the spectroscopic sample. Moreover, as our galaxy classifications are based only on observed $B-R$ colors, the good match to the I, U, and g counts gives us an independent check on the validity of our LF models.

However, an important caveat needs to be kept in mind, namely the sensitivity of the LF evolution results to the precise choice of SED's used to classify galaxies. In particular, the present choice of non-evolving SED's obviously does not account for the color evolution of galaxies. If one were to use more physically motivated *evolving* SED's, the resulting galaxy classifications will generally be different. For example, one can eliminate the negative density evolution of early-type galaxies by using simple evolving models with exponentially declining star formation rates (Bruzual & Charlot 1993), wherein galaxies are bluer at higher redshifts; this allows more galaxies to be classified as early-type at higher z, and thus increases the value of P. There are obviously many possible combinations of evolving SED's that one may choose, by varying parameters such as star formation rate, age, metallicity, or dust content. Work is ongoing to test particular evolutionary scenarios, for example, to see whether simple pure luminosity evolution models (no density evolution), with various choices of star formation history, age, etc., are consistent with both the CNOC2 LF and number count data. (The availability of 5-color data for all CNOC2 galaxies will be of great help here, as it permits tight constraints on the SED of any particular galaxy.) The LF evolution model outlined in the present paper should thus be considered as a first step, a *description* of galaxy evolution within the framework of non-evolving SED's, rather than an *explanation* of galaxy evolution in terms of more physically motivated evolving models.

We will also be able to constrain those physical models using additional tools. Note that there is much spectroscopic information available, which will permit measurements of star formation rates using emission line indices, as well as classification of galaxies via principal component analysis. Moreover, photometric redshifts can be accurately calibrated using the spectroscopic sample, and use of a larger photometric-redshift sample will help to constrain the LF at fainter magnitudes, as well as reduce errors on the P and Q parameters. Measurements of the evolution of the surface brightnesses and morphologies of CNOC2 galaxies will also be possible. Finally, the environmental dependence of luminosity and star formation properties, and the relation to the evolution of galaxy clustering, will be explored using catalogs of groups and pairs of galaxies, and through measurements of the correlation function by galaxy type. Ultimately we hope to put clustering, luminosity, star formation, and spectral properties together into a coherent and self-consistent picture of galaxy evolution at moderate redshifts $z < 1$.

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