The Luminosity Function for $L > L^*$ Galaxies at $z > 3$

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Abstract

Through use of multiband (U, B_J, R_F, I_N) photometry we have isolated high redshift (3.0<z<3.5) galaxy candidates in a survey of 1.27 deg^2 to $R_F = 21.25$ and a survey of 0.02 deg^2 to $R_F = 23.5$. Our pool of candidates constrains the nature of the $3.0 < z < 3.5$ luminosity function over the range $L^* \lessapprox L \lessapprox 100L^*$, if we grant a similar level of completeness to these data as for very faint samples (to $R = 25.5$) selected in a similar fashion. Our constraints agree with the high redshift sky density at $R_F = 20.5$ estimated from Yee *et al.* 's (1996) serendipitous discovery of a bright, $z = 2.7$ galaxy, as well as the density at $R_F \approx 23$ by Steidel *et al.* (1996b). We strongly rule out – by more than two orders of magnitude at $M_{R_F} = -25$ – the $L > L^*$ luminosity function for $z = 3 - 5$ galaxies obtained by a photometric redshift analysis of the Hubble Deep Field (HDF) by Gwyn & Hartwick (1996). Our results at $R_F \approx 23$ are more consistent with the photometric redshift analysis of the faint HDF galaxies by Sawicki & Yee (1996), but our present upper limits at the brightest magnitudes ($R_F < 21.5$, $M_{R_F} < -24$) allow more generous volume densities of these super-L^* galaxies.

Subject headings: galaxies: luminosity function – galaxies: evolution – galaxies: distances and redshifts

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1. Introduction

When deep imaging surveys revealed a significant population of blue objects (well in excess of no-evolution models) at $B > 23$, it was initially thought (Tyson 1988, Cowie 1988, Cowie *et al.* 1988) that this could be the signature of "primeval galaxies" (PGs) – counterparts to present day $\approx L^*$ galaxies undergoing an initial, extremely bright burst of star formation at high z (Partridge & Peebles 1968). Ever deeper redshift surveys (now $B \sim 24$, Songaila *et al.* 1994, Glazebrook *et al.* 1995), however, revealed galaxies only to $z < 0.8$, and it became evident that galaxies with redshifts as high as 3 were not likely to represent a substantial fraction of the galaxies, even to $B \sim 25$ (Koo *et al.* 1996).

The conspicuous paucity of faint, high z galaxies had already been shown by two studies of faint galaxy *colors*. At $2.7 < z < 3.4$, galaxies should exhibit a particularly red $U - B$, compared to a rather blue color at longer wavelengths, because of the presence of the Lyman limit in the U passband. The first application of this test by Koo, Kron & Majewski (see Majewski 1988, 1989) demonstrated the number of $B < 24.5$ galaxies showing the expected $z > 3$ color signature to be negligible – $< 1\%$. With deeper data, Guhathakurta, Tyson & Majewski (1990) showed that the number of galaxies to $B \sim 27$ showing the expected $z > 3$ color signature was no more than 7%, and likely $< 1\%$ of galaxies.

More recently, Steidel *et al.* (1995 and references therein, "S95") have repeated the "Lyman limit imaging" experiment over ~ 0.03 deg^2 to their $\Re = 25.5$. They confirm the relatively low surface-density of high z candidates, and with the Keck 10-m have spectroscopically verified 22 of 37 color-selected candidates are indeed at $3 < z < 3.5$ (Steidel *et al.* 1996b, "S96"). All galaxies in S96 have $\Re$ =23.7-25.5, implying luminosities near present day L^* and slightly brighter. From their data, S96 estimate the comoving space density of these objects to be approximately 1/2 that of present day $L > L^*$ galaxies. Both Steidel *et al.* (1996a) and Lowenthal *et al.* (1997) find comparable results in the same magnitude and redshift range in the Hubble Deep Field (HDF), despite more liberal color selection in the latter survey.

The numbers of objects much brighter than L^* is less well constrained. Yee *et al.* (1996) have discovered serendipitously a "normal" (i.e., neither AGN nor radio), $V = 20.5$ galaxy at $z = 2.7$. Though super-luminous at $M_R - 5 \log h \approx -25$ (q_0=0.5, $h = H_0/100$), this galaxy is spectroscopically similar to the S96 galaxies. Based on one galaxy in their 0.66 deg^2 survey, Yee *et al.* estimate the density of such objects at $R \sim 20$ is $10^{0 \pm 1}$ deg^{-2}.

Meanwhile, Gwyn & Hartwick (1996, "GH") attempted to determine *photometric* redshifts for galaxies in the HDF and claim dramatic changes in the galactic luminosity function ($\Phi(M)$) from $0 < z < 5$ with $\Phi(M)$ becoming flat between $-24 \leq M_B \leq -15$ for

$3 < z < 5$. They predict a substantial *abundance* of galaxies up to $M^* - 4$ at high z. In stark contrast, the photometric redshift analysis of the HDF by Sawicki *et al.* (1996, "SLY") finds a more prosaic $z = 3 - 4$ luminosity function, adequately described by a Schechter function with $\alpha = -1.3$ and $\phi^* = 0.023h^3$ Mpc^{-3}. An extrapolation of this function predicts many orders of magnitude less high z galaxies at $R_F = 21$ than GH. Yet another photometric analysis of the HDF by Mobasher *et al.* (1996) suggests strong luminosity function evolution to $z = 3$, and implies numbers of bright $z = 3$ galaxies intermediate between GH and SLY. While all of these groups suggest that in the HDF they are seeing the formation of $L \geq L^*$ galaxies at high z, there seem to be vast differences in the implied nature of the luminosity function, especially for bright galaxies.

The range in HDF results may be attributable to the substantial uncertainty in the application of photometric redshifts at very faint magnitudes. Unlike the photometric redshift study of brighter galaxies by Connolly *et al.* (1996), at HDF depths there is no adequate spectroscopic training set available for calibration. While S96 have a handful of spectra of $z > 3$ galaxies, the vast majority of objects to $\Re \approx 25$ and beyond are without spectroscopic redshifts. Most troubling to the interpretation and application of spectro-photometric galaxy models is the near-degeneracy in color between particular redshifts (e.g., at $0 < z < 1$ for the bluest galaxies and $z \approx 2.5$ for all galaxies; see figure 1); this plausibly produced the apparent strong bimodality in the redshift distribution inferred by GH. Unlike in Connolly *et al.* , GH and SLY do not use apparent brightness to break such degeneracies in the redshift estimates. Moreover, as pointed out by SLY, differences in the model spectral energy distributions (SEDs) – particularly in the still poorly understood rest-frame ultraviolet where internal reddening and intervening absorption are important – lead to substantially different results. It is important, therefore, to check the HDF results, especially at magnitudes where spectroscopic confirmation is feasible.

Apart from the S96 data near L^* and the loose Yee *et al.* (1996) constraint, there is scant spectroscopic redshift data to explore the nature of the luminosity function of $z > 3$ galaxies. Ironically, it is $\Phi(M)$ at magnitudes brighter than those explored by S96 that is most poorly defined due to a lack of reliable data; if the high redshift $\Phi(M)$ is of prosaic form, with a steep decline toward the bright end, much larger survey areas are required to explore the $L >> L^*$ domain than have been achieved with CCD surveys to date. We have undertaken a large area, photometric search for bright, high z galaxies. Even without spectroscopy, we constrain the high z luminosity function based on the magnitude distribution of our high z candidates. To do so, we rely on the good correspondence between high z galaxy candidates identified by S95 through similar selection criteria and *bona fide* high z galaxies among these candidates as confirmed by S96.

2. High Redshift Galaxy Search

Our search for bright, $z > 3.0$ galaxies utilizes two sets of multicolor galaxy catalogues. The first data set consists of the photographic catalogues generated for the Kitt Peak Galaxy Redshift Survey (KPGRS; Munn *et al.* 1997) and faint quasar surveys (Kron *et al.* 1992). These catalogues cover four separate regions of the sky totaling 1.27 $\deg^2$ with photometry from sky-limited, Mayall 4-m photographic plates in the $UB_JR_FI_N$ passbands[7] calibrated with deep CCD photometric sequences (e.g. Majewski *et al.* 1994). While these catalogues reach to $R_F = 23$, we choose here a conservative catalogue limit of $R_F = 21.25$, where random errors in B_J, R_F and I_N are at most 0.3 mag (smaller than the color difference between our $z > 3$ selection thresholds and the locus of low z galaxies).

The panels in Figure 1 show the progression of $U - B_J$, $B_J - R_F$ and $R_F - I_N$ galaxy colors with redshift. The iso-z loci for different galaxy types were generated with Bruzual & Charlot's (1993) models for a range of star-formation histories[8], plus observed elliptical and starburst (using the galaxy N4449) spectral energy distributions (SEDs). Model and observed SEDs were reddened as a function of band and redshift to account for intervening absorption (only), as prescribed by Madau (1995). This process is identical to that in S96, except that we include a broader range of SEDs. For colors of $z > 3.0$ galaxies this has little consequence, however it is important at lower redshifts. Based on our models, dashed lines delimit the region of each color-color diagram inhabited by $z > 3.0$ galaxies. To justify this selection, we show (top-left panel, Figure 1) the S96 $z > 3.0$ galaxies in our UB_JR_F system using the transformations in Majewski (1992) and Steidel & Hamilton (1993); the symbols are coded for those objects S96 classified as "robust" (U-band drop-outs falling within the selection boundary based on 1-σ limits), and "marginal" (non-"robust" objects within the selection boundary). We also show (top-right panel, Figure 1) all known $2.7 < z < 3.0$ and $z > 3.0$ QSOs in our fields (Kron *et al.* 1992).

The middle and right panels of Figure 1 show our $R_F < 21.25$ sample. We are interested in setting upper limits on the numbers of bright, high z galaxies; our selection algorithm reflects a liberal acceptance threshold that sets a conservative upper limit on $\Phi(M)$ while maintaining reasonable reliability. As a first acceptance criterion, we adopt a

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[7]Our U band is virtually identical to the standard photoelectric U (Koo 1985). Steidel & Hamilton's (1993) U_n is about 100 Å bluer, and U_{F300W} for the HDF is about 700 Å bluer.

[8]Colors are for evolving and non-evolving model galaxies with 16 Gyr ages at $z = 0$ (q_0=0.1, H_0=50 km s^{-1} Mpc^{-1}, Λ=0), Salpeter initial mass, and $0.01 < \mu < 0.95$, where μ is the fraction of galactic mass in stars after 1 Gyr of star formation.

similar selection function to S96 – objects with red $U - B_J$ and blue $B_J - R_F$ colors, as illustrated in the top row of Figure 1. However, our models show the $U - B_J, R_F - I_N$ diagram (middle row, Figure 1) affords a much cleaner separation of high z galaxies from the low z locus. We accept high z galaxy candidates from this diagram as well. Galaxies selected in the ($U - B_J$, $B_J - R_F$) and ($U - B_J, R_F - I_N$) diagrams need not be the same. For example, a high z galaxy might be missed in the $U - B_J, B_J - R_F$ plane if the line of sight to that object passes through a sufficient number of neutral hydrogen clouds for significant suppression of the observed B_J flux (with both $U - B_J$ and $B_J - R_F$ affected).

The $B_J - R_F$, $R_F - I_N$ diagrams in the bottom panels of Figure 1 reveal the high z locus is not as well separated as in the other diagrams. As a compromise between completeness and low z contamination (reliability), we (1) adopt a more conservative color cut, but (2) accept galaxies in this diagram only if they are *bona fide* U band drop-outs. Objects selected in this way satisfy the relevant $R_F - I_N$ color criterion in the ($U - B_J, R_F - I_N$) diagram, but have $U - B_J$ upper limits insufficient to place them confidently within the $z > 3$ region. These objects are faint in B_J, so their exclusion in the middle panel is likely due only to the magnitude limit of the U plates. Hence these are plausible $z > 3$ candidates. In the $B_J - R_F, R_F - I_N$ diagrams we have the potential to discover galaxies at redshifts even higher than 3.5, yet no such "B_J-band drop-outs" were found.

Each high z candidate was inspected visually on a number of photographic plates to ensure reliability. We find twelve *resolved* (unlikely to be either stars or QSOs) $z > 3.0$ candidates between $19.25 < R_F < 21.25$. We also find 20 *unresolved* sources with $R_F < 21.25$; three are spectroscopically identified as $z > 2.9$ QSOs and two as stars in our QSO survey (Kron *et al.* 1992). No galaxies at $z > 1$ have been identified among any of the QSO candidates in Kron *et al.* (1992).

To bridge our study of the high z luminosity function from $R_F = 21.25$ to the very deep S96 sample, we have generated deeper images in two 39 arcmin^2 subfields of SA 57 by stacking PDS microdensitometer plate scans of five U plate images, ten B_J plate images and five R_F plate images (see Majewski 1988). Candidate $z > 3$ galaxies are selected here only on the basis of $U - B_J, B_J - R_F$ as before (no comparably deep I_N image was available). A total of 11 candidates (both stellar and nonstellar) are found (small triangles in top-middle panel of Figure 1) to the conservative limit of $R_F = 23.5$.

3. High Redshift Luminosity Function

Our $z > 3$ galaxy candidates represent the highest possible density of bright, S96-like galaxies if we assume a similar level of completeness in our sample as has been assumed for S96. We believe no $z > 3$ galaxies lie within our unresolved sample to $R_F < 21.25$, but, in the spirit of upper limits, we include discussion of this sample here. Our survey should be *more* complete than, for example, S96 since we utilize multiple combinations of colors. If there exists a population of high z galaxies not chosen by our selection criteria, our comparison to other surveys using similar S96-like selection criteria is still valid.

In Figure 2 we compare the various studies of the $z > 3$ luminosity function in a cosmologically model-independent way:

(i) The luminosity functions of GH (in the range $3 < z < 5$) and SLY (in the range $3 < z < 4$) are transformed into the apparent differential counts $\mathrm{A}(R_F)$ for galaxies lying in the redshift shell between 3 and 3.5, the range of redshift to which our data apply. To do this we have adopted their respective cosmologies to scale by the appropriate volumes and luminosity distances, and assumed k-corrections for N4449. The observed spectrum of N4449 has been extended below 1250 Å using the best-matching Bruzual & Charlot model in the range 1250-2000 Å. Note that GH and SLY calculate "the $z > 3$ luminosity function" beyond our $z = 3.5$ limit, yet both studies find the space density falling rapidly beyond $z \approx 2$. Thus our estimation of the predicted $\mathrm{A}(R_F)$ for their $\Phi(M_{R_F})$ in the *lowest* redshift shell of their broader z ranges provides *lower* limits on the counts. This is particularly relevant to the gross discrepancy between our derived *upper limits* to $\mathrm{A}(R_F)$ and the GH results (presented as *lower* limits) detailed below.

(ii) Candidate $z > 3$ galaxies at faint magnitudes were compiled from S95 and S96 in two ways. a) In S95, four of five fields had well-defined samples and areas (i.e. excluding Q0000-263), yielding 15 candidates in 20.7 arcmin^2 to $\Re < 25.5$ defined as "robust" by them. From S96, we counted candidate and confirmed $z > 3$ galaxies in two fields (Q0000-263 and SSA 22) to the same depth in a total area we estimate to be 45.4 arcmin^2. These tallies exclude spectroscopically confirmed stars, QSOs, or galaxies at $z < 3$. A total of 36 robust candidates in 66.1 arcmin^2 are counted, 22 of which are spectroscopically confirmed. Based on the 81% reliability of spectroscopically identified candidates (3 of 16 are QSOs) we scaled the remaining unconfirmed robust candidates to derive number counts in the R_F band for $z > 3$ galaxies. b) For S95, we have counted, in the same 4 of 5 fields, additional objects not considered "robust" but still within the color region believed to contain $3 < z < 3.5$ galaxies. This yielded 23 candidates (including "robust" ones) in 20.7 arcmin^2.

(iii) We include the $z = 2.7$ Yee *et al.* as a datum at $R_F \sim 20.35$ assuming one source in their survey area at this apparent brightness.

Without redshifts, we constrain the density of *resolved* $z > 3.0$ galaxies to $\leq 10 \pm 3$ deg^{-2} at $R_F < 21.25$, or $\leq 22 \pm 4$ deg^{-2} if we include *unresolved* candidates (minus the known QSOs and stars). Our counts are in strong conflict – at least two orders of magnitude – with GH at this depth. We note that the counts of $z > 3$ galaxies in the GH analysis rivals our *total* galaxy counts for $R_F < 22$ (Figure 2), although if we had adopted redder k-corrections, the results of the surveys would be in somewhat better agreement. At $22 < R_F < 23.5$, our limits are similar to the upper limits of the more liberal set of the fainter S96 candidates ([ii]b above). The combination of the S96 upper limits and our limits at brighter magnitudes suggests a rapid decline in the $z > 3$ luminosity function brighter than $M_R - 5\ log\ h \approx -20.5$ to -21. This corresponds to the SLY *et al.* M^* at $z = 3.25$ ($R_F = 24.5$), or $\approx$0.75 mag brighter than the local galaxy luminosity function. In general, our upper limits and those derived from S95 agree with the SLY luminosity function for $23.5 < R_F < 25$. However, over the brighter range of our survey, $19 < R_F < 23.5$, our upper limits allow for a much more gradual bright-end decline than suggested by the SLY extrapolation, and are consistent with the Yee *et al.* (1996) serendipitous discovery.

While the SLY luminosity function overestimates the numbers of robust candidates from S95 and S96, our more liberal selection from their data is marginally consistent to $R_F \approx 25$. However, it is critical to discriminate between the SLY suggestion of a rising faint end of the luminosity function and the flatter faint end hinted at by the S96 data. Upper limits on the shape of the $L < L^*$ luminosity function could be checked via the U-band drop-out method in a similar manner to what we have done here at brighter magnitudes. While the HDF data are appropriately deep for such an exercise, the U_{F300W} of WFPC2 is much bluer than ground-based, Johnson U; this increases the sensitivity of HDF data to $z \sim 2.2$ and complicates direct comparisons. Hence there is a need for ultra-deep imaging in the Johnson U band even over relatively small fields of view.

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FIG. 1. – $U - B_J, B_J - R_F, R_F - I_N$ color-color diagrams. Left panels: the locus of non-evolving observed, model, and passively evolving model galaxy colors (see key in middle-left panel) as a function of redshift (labels, connected by dotted lines of constant z); our $z > 3$ color-selection (long-dashed lines); the $3 < z < 3.5$ samples from S95 and S96, transformed to our photometric system (top-left); and the Yee *et al.* datum, transformed from their g, V, r, I bands using relations from Fukugita *et al.* (1995; bottom-left). Middle panels: **our sample** of all galaxies (points) and extended high z candidates to $R_F = 21.25$ and high z candidates from stacks of photographic plate images to $R_F = 23.5$. Right panels: **our sample** of all stellar sources (points), stellar high z candidates to $R_F = 21.25$, and confirmed QSOs and stars. Keys in middle and right panels apply to all middle and right panels. Note the significant number of our candidates in the same region of color-space as S96's confirmed $3.0 < z < 3.5$ sample. We select high z candidates, however, using *all three* color-color diagrams.

FIG. 2. – Differential counts of candidate and confirmed $3 < z < 3.5$ galaxies from figure 1, as described in text and key. Error bars enclose 68.3% confidence intervals (Gehrels 1986). Also shown (lines) are counts for $3 < z < 3.5$ galaxies from luminosity functions inferred from the HDF via photometric redshifts (GH and SLY). The dotted portion of SLY is an extrapolation of their best-fitting Schechter function. The absolute magnitude scale at $z = 3.25$ is shown at the top, while the change in R_F with redshift for constant luminosity and q_0=0.5 is shown at the bottom. *Total* R_F galaxy counts from Kron (1980) and Majewski (1988) are shown for reference.

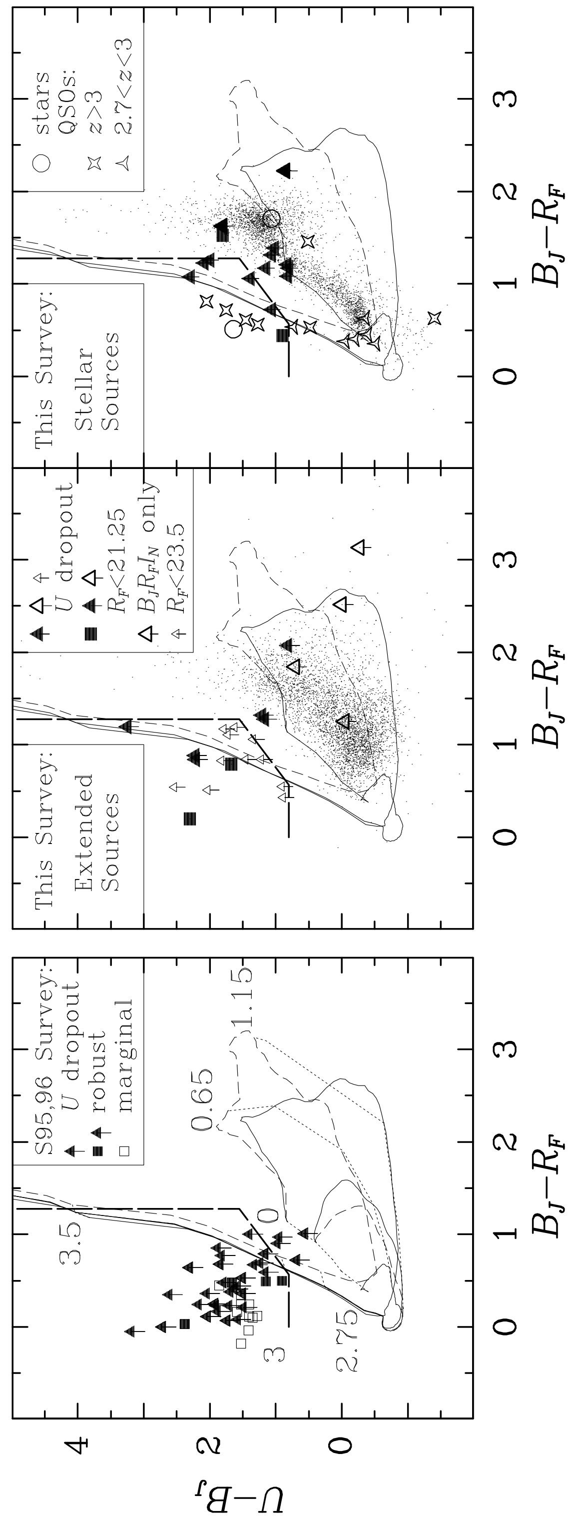

Figure 1 (top panel) Bershady *et al.*

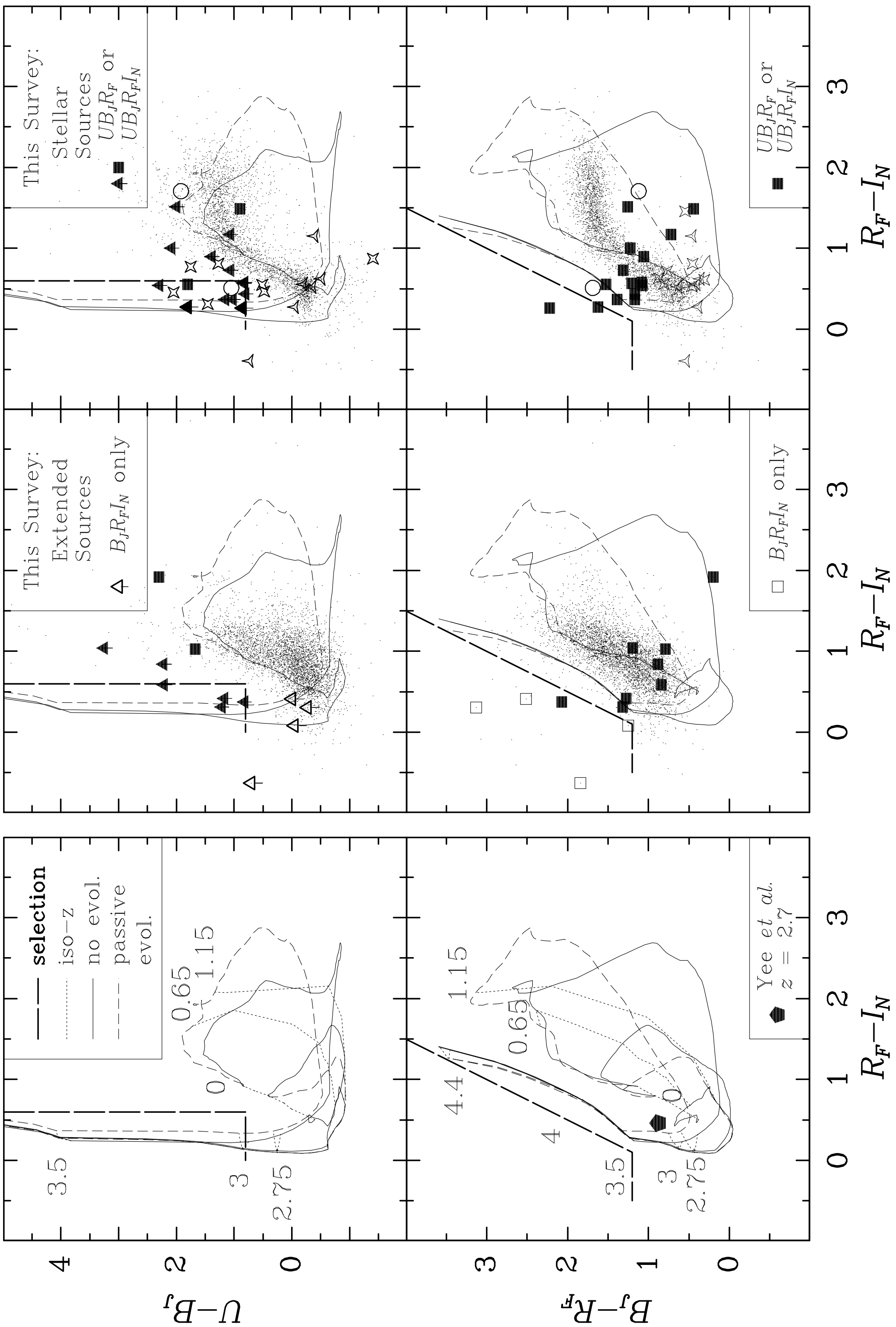

Figure 1 (bottom panels) Bershady *et al.*

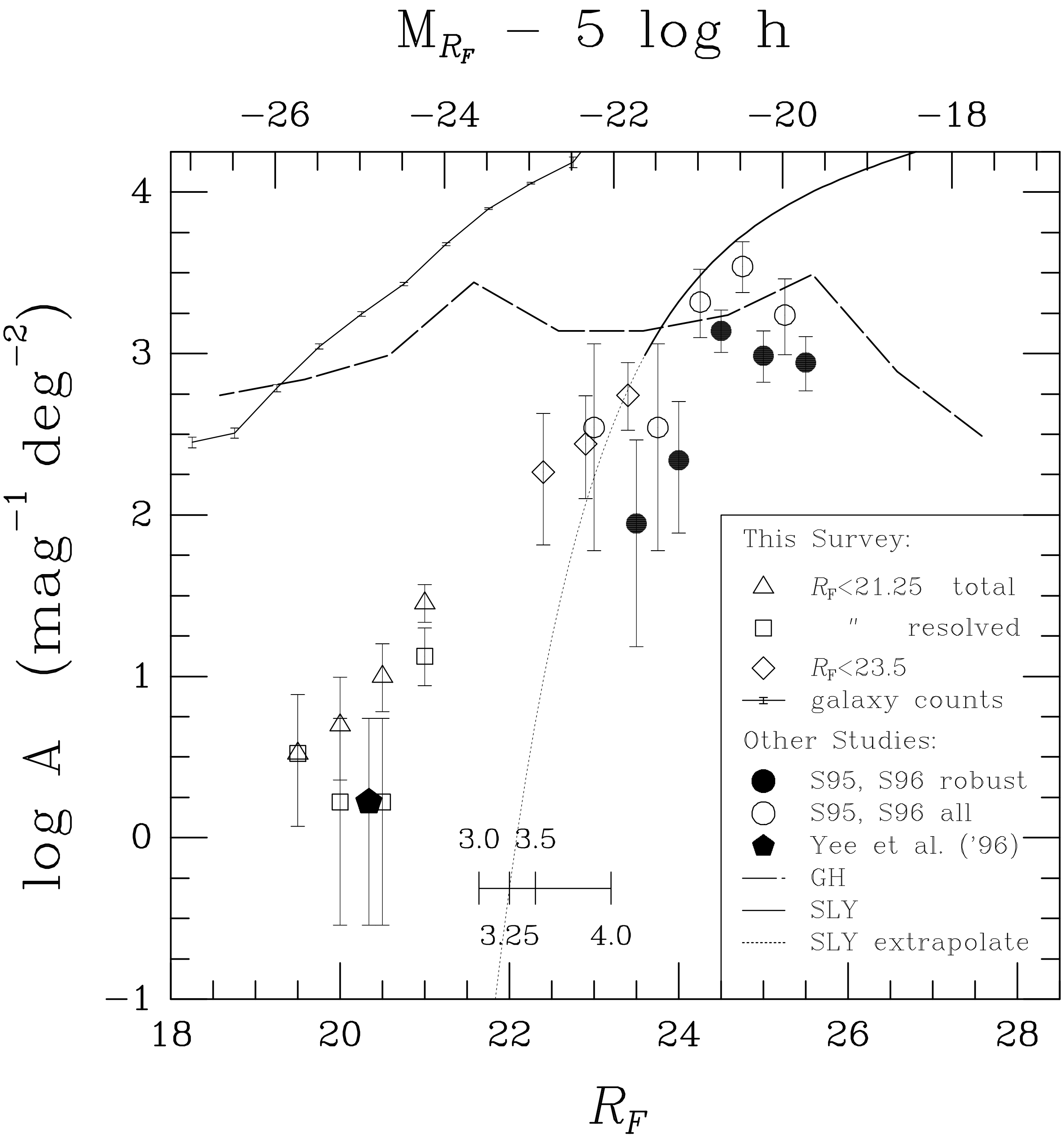

Figure 2 Bershady *et al.*