Galaxies and Large Scale Structure at $z \sim 3$

C. Steidel$^1$, K. Adelberger$^1$, M. Giavalisco$^2$, M. Dickinson$^3$, M. Pettini$^4$, and M. Kellogg$^1$

Abstract. We summarize the status of a “targeted” redshift survey aimed at establishing the properties of galaxies and their large scale distribution in the redshift range $2.5 < z < 3.5$. At the time of this writing, we have obtained spectra of more than 400 galaxies in this redshift range, all identified using the “Lyman break” color–selection technique. We present some of the first results on the general clustering properties of the Lyman break galaxies. The galaxies are very strongly clustered, with co-moving correlation length similar to present–day galaxies, and they are evidently strongly biased relative to the mass distribution at these early epochs, which is consistent with hierarchical galaxy formation models if Lyman break galaxies trace the most massive halos at $z \sim 3$. Prospects for large surveys for galaxies beyond $z \sim 4$ are discussed.

1. Introduction

At the time of this writing (December 1997), it has been slightly more than 2 years since the “Lyman break” technique (discussed extensively elsewhere, e.g. Steidel & Hamilton 1993, Steidel, Pettini, & Hamilton 1995, Madau et al. 1996, etc.), for isolating large numbers of high redshift ($z \sim 3$) galaxies was demonstrated to work efficiently, based on confirming spectra obtained at the W.M. Keck Observatory (Steidel et al. 1996). Galaxies at $z \sim 3$ or greater are no longer terribly surprising, as now the highest redshift galaxy has $z = 4.92$ (Franx et al. 1997) and it probably won’t be very long before the $z = 5$ barrier is surpassed. However, as exciting as finding distant galaxies can be, the greatest gains for our understanding of the galaxy formation process will come from the feasibility of assembling large samples of galaxies at previously inaccessible redshifts, and to study their properties and distribution with a high level of statistical significance. In view of this, we have spent the ensuing 2 years compiling a large sample of $z \sim 3$ Lyman break galaxies, selected in a consistent manner over a number of relatively large fields. Our aim in carrying out this survey is to obtain $\sim 100+$ redshifts per field in each of 5–6 fields, each of size

$^1$Palomar Observatory, Caltech 105-24, Pasadena, CA 91125, USA
$^2$Carnegie Observatories, 813 Santa Barbara St., Pasadena, CA 91107, USA
$^3$The Johns Hopkins University, and STScI, 3700 San Martin Drive, Baltimore, MD 21218
$^4$Royal Greenwich Observatory, Madingley Road, Cambridge CB3 OEZ, UK
160 square arc minutes or greater. We anticipate that the present survey will
reach completion by the end of 1998.

Our survey for Lyman break galaxies continues to be based upon deep
ground–based images obtained in a custom broad–band filter system, $U_nGR$.
For reliable identification of high redshift galaxy candidates, we have found that
long integrations on 4m–class telescopes are required to reach adequate depth
and S/N; most of our images have been obtained at the prime focus of the
Palomar 5m telescope, and a high quality data set for a 9′ by 9′ field of view
requires about 12 hours of total integration time (7 hours in the $U_n$ band alone),
or about two good nights of observing. The identification of candidate $z \sim 3$
galaxies is based upon a combination of the modeling of the spectral energy
distributions of high redshift star–forming galaxies, including the effects of the
opacity of the galaxy ISM and the intergalactic medium (cf. Madau 1995),
and the results of our spectroscopy, which have resulted in a somewhat modified
color–selection window as compared to the purely theoretical one which was used
originally (cf. Steidel, Pettini, & Hamilton 1995). Figure 1 shows a two–color
diagram from one pointing of the Palomar 5m, indicating the region from which
we select our samples of Lyman break galaxy candidates. Approximately 5% of
all galaxies to $R = 25.5$ are candidate high redshift ($2.5 < z < 3.5$) galaxies.

2. Spectroscopic Results

All of the follow–up spectroscopy has been obtained using the Low Resolution
Imaging Spectrograph (LRIS) (Oke et al. 1995) on the W.M. Keck telescopes.
On a typical slit mask, we can obtain $\sim 20$ spectra of candidate $z \sim 3$ galaxies;
our current configuration generally leads to $\sim 80\%$ of the observed galaxies
yielding redshifts. A clear night will yield a total of $\sim 50$ $z \sim 3$ galaxies. The
current redshift histogram for objects satisfying the color criteria in the shaded
region of Figure 1 is shown in Figure 2; about 90% of the galaxies fall in the
redshift interval $2.6 \leq z \leq 3.4$, with none having $z < 2.2$.

The success of the spectroscopic follow–up, and the well-established redshift
selection function for our particular color selection criteria, allow a number of
inferences based on the statistics of the larger photometric sample, which at the
time of this writing includes $\sim 1400$ Lyman break galaxy candidates in a total
survey area of about 0.25 square degrees. For comparison to our earlier results
prior to most of the spectroscopy, the surface density of Lyman break galaxies
having the redshift distribution shown in Figure 2, and brighter than $R = 25.0$, is
1.0 arcmin$^{-2}$, or roughly 2.5 times larger than our initial (conservative) estimates
of the surface density of high redshift galaxies. Clearly, these numbers are
sensitive to the exact color cut adopted, and the choice of limiting magnitude.
We have converged on the color selection region illustrated in Figure 1, and our
photometry allows reasonably complete identification of $z \sim 3$ Lyman break
galaxies to $R = 25.5$. We will discuss details of the redshift selection function,
and the space density and luminosity distribution of the LBGs, in Dickinson et
al (1998).

The combination of the photometry and the follow–up spectroscopy also en-
ables us to attempt an object–by–object extinction correction, by “de-reddening”
each galaxy to the spectral energy distribution expected for an unattenuated ac-
Figure 1. An example of a two–color diagram used to select Lyman break galaxies for follow–up spectroscopy. The shaded region corresponds to the region from which candidate Lyman break galaxies are selected. Of the $\sim 3300$ objects in the field to $R = 25.5$, approximately 170 of them satisfy our adopted color criteria. Triangles represent objects for which the $U_n - G$ color is a lower limit.
Figure 2. Redshift histogram of spectroscopically confirmed Lyman break galaxies in our \( z \sim 3 \) survey. The median redshift is \( \langle z \rangle = 3.02 \). The redshift cutoff near \( z \sim 3.4 \) is a result of our color selection criterion in \( G - R \), while the lower redshift cutoff is imposed by the requirement that a significant “break” must be present between the \( U_n \) and \( G \) passbands (cf. Fig. 1).

Figure 3. “De-reddening” the observed Lyman break galaxies, and the effects on the inferred star formation rates. The left panel shows uncorrected UV luminosities translated into inferred star formation rates; the middle and right panels show corrected versions using two different reddening/extinction laws.
tively star–forming galaxy (further details and results will be presented in Dickinson et al 1998) placed at the known redshift. By far the largest uncertainty in doing this is the adopted reddening/extinction model; as can be seen in Figure 3, the net correction to the observed population of galaxies in terms of implied star formation rate ranges from a factor of ∼ 2 if an SMC–like reddening curve is adopted, to a factor of ∼ 8 for the assumption that the empirical starburst galaxy extinction law of Calzetti (1997) is more appropriate. We believe that these two reddening laws probably bracket the “truth”, although it will take much more work to establish the importance of extinction with any certainty. For example, we are in the process of obtaining near–IR spectra (rest–frame optical) of a sub-sample of Lyman break galaxies (Pettini et al 1998), which will provide a cross-check on the appropriate extinction corrections using the luminosity of nebular emission lines. Rest–frame far–IR (observed sub–millimeter) observations of the same galaxies are obviously of interest.

3. The Clustering of z ∼ 3 Lyman Break Galaxies

One of our main goals in undertaking a large survey of galaxies at z ∼ 3 was to investigate the large–scale distribution of star–forming galaxies at such early epochs. Some of the preliminary results of our spectroscopy have been published in Steidel et al. (1998), in which the implications of a large structure of galaxies at z = 3.09 were discussed. The results of using the photometric sample, together with the well–established redshift selection function, for an analysis of the angular clustering of z ∼ 3 Lyman break galaxies are presented in Giavalisco et al (1998). A count–in–cells analysis of the survey fields in which we have completed our spectroscopy will appear in Adelberger et al (1998).

The most striking (and robust) result at present is that the Lyman break galaxies must be much more clustered than the overall mass distribution on scales of ∼ 10h⁻¹ Mpc, for any reasonable cosmological model. Within the context of Cold Dark Matter models for the formation of structure, this strong “bias” (we measure an effective linear bias parameter of b ≈ 6 for Ω_m = 1 and b ≈ 2 for Ω_m = 0.2) is expected if the LBGs are tracing relatively massive dark matter halos, with M_h ∼ 10^{12} M⊙ or greater. In hierarchical models, because halos with such large bias would be expected to be tracing the densest environments at z ∼ 3, the LBGs are probably the progenitors of objects that end up in groups and clusters of galaxies by the present day (Governato et al 1998, Wechsler et al 1998). As can be seen in Figure 4, large structures in redshift space are relatively common features, as we had asserted in Steidel et al. (1998); the largest peaks are expected to become Coma–like clusters of galaxies by z ∼ 0 (see the article by Carlos Frenk in these proceedings). The co–moving correlation length for Lyman break galaxies at z ∼ 3 is r_0 ≈ 4(6)h⁻¹ Mpc for Ω_m = 1.0(0.2); note that this is as large or larger than that of present–day galaxies. This fact points out the danger in interpreting the evolution of galaxy correlation functions from deep redshift surveys as being indicative of the overall growth of structure by gravitational instability; samples of galaxies at generally smaller redshifts have much smaller co–moving correlation lengths (Carlberg et al 1997, Le Févre et al 1996). This probably results from the complicated and model–dependent interplay between effective linear bias of halos in which
Figure 4. Field–by–field redshift histograms from 4 of our survey fields. DSF2237 and SSA22 are 9′ by 18′ fields, whereas HDF and CDF are (at present) only single 9′ by 9′ fields. Note that there is at least one highly significant redshift–space “structure” per field. The most significant features are likely to be concentrations that will become moderately rich clusters by the present epoch. The variance in the redshift histograms (relative to the selection function, which is shown with the dotted curve in each panel) provides a direct measure of the galaxy fluctuations on ~ 10 Mpc scales, which can be compared with the fluctuations in the mass expected for various assumed cosmologies.
galaxies have formed, and the (photometric) observational biases imposed by the means by which the galaxies were selected, all of which are expected to be redshift–dependent. In any case, the paradigm that galaxies form at high peaks in the density field at early epochs that would be biased with respect to the overall mass distribution is strongly supported in our data, and the observations are able to specify the spatial distribution of observable galaxies at early epochs, for comparison to models which include both the dark matter component and recipes for star formation (e.g., Kauffmann 1998; Frenk 1998). We are currently exploring more accurate statistics using our growing sample that can be used to test various flavors of hierarchical models. At present, combining information on the clustering properties and the observed abundance of LBGs constrains the shape of the power-spectrum from galaxy to cluster scales, and favors a universe with low overall matter density within the context of CDM models (Adelberger et al 1998). It also suggests a very tight relationship between dark matter halo mass and UV luminosity. We hope to have much more to say on such matters in the very near future.

4. Prospects for Galaxy Surveys at \( z > 4 \)

In the process of obtaining the data for the \( z \sim 3 \) sample, we have recently begun exploring the use of Lyman break color selection for a higher redshift sample, with an expected median redshift \( (z) \sim 4.2 \). In this case, the color selection is accomplished simply by adding an observed \( i \) band (\( \lambda_{\text{eff}} \) = 8100 Å) for those fields in which we already have deep \( G \) and \( R \) images. In order to make strong claims about possible evolution of the star forming galaxy populations between \( z \sim 3 \) and \( z \sim 4.2 \), it will be essential to establish an accurate redshift selection function. Our initial forays into the spectroscopy of such candidates have been very instructive. First, it certainly does work to use similar color–selection for this higher redshift range (at the time of this writing we have confirmed 10 redshifts in the range \( 3.9 \leq z \leq 4.5 \)), but it will be far more difficult to obtain large galaxy samples at these redshifts as compared to \( z \sim 3 \). This is partly due to a real decline in space density at a given luminosity (our preliminary indications are that the abrupt decline beyond \( z \sim 3 \) as suggested in the HDF [Madau et al. 1996] is supported by our ground–based data over much larger fields), partly due to a slightly fainter apparent magnitude for a given absolute luminosity, but mostly to the fact that the night sky background becomes much more troublesome when the lines which one generally uses to secure the redshifts appear much farther to the red. One of the consequences is that galaxies without strong Lyman \( \alpha \) emission lines are exceedingly difficult to identify securely.

5. The Future

It is clear that galaxies at very early epochs (the first 10% of the age of the universe) are now open to the kinds of wholesale, statistical studies that will provide significant constraints on models of galaxy and structure formation. Issues that have clearly arisen at this meeting as being very important are 1) to what extent is dust altering our view of star formation in early galaxies, and therefore our census of the global star formation history of the universe?
2) What are the clustering properties of early galaxies really telling us about cosmological world models and/or how the galaxy formation process works? 3) What are the present day descendents of star forming galaxies seen at very high redshift, and more generally how do objects observed at one cosmic epoch relate to those observed at another? 4) How are dark matter halos and observable galaxies related to one another? The rapid developments on both observational and theoretical fronts, many of which have been discussed at this meeting, will almost certainly lead to a great deal of progress on these and other fundamental questions in just the next few years.

References

Adelberger, K. L., Steidel, C. C., Giavalisco, M. Dickinson, M., Pettini, M., & Kellogg, M. 1998, ApJ, in press.
Calzetti, D. 1997, in The Ultraviolet Universe at Low and High Redshift, ed. W. Waller (Woodbury: AIP Press), in press [astro-ph/9706121].
Carlberg, R. G., Cowie, L. L., Songaila, A., & Hu, E. M. 1997, ApJ, 484, 538
Dickinson, M., et al. 1998, in preparation.
Franx, M., Illingworth, G. D., Kelson, D. D., Van Dokkum, P. G., & Tran, K-Y. 1997, ApJ, 486, L75
Frenk, C. S. 1998, this volume.
Giavalisco, M., Steidel, C. C., Adelberger, K. L., Dickinson, M., Pettini, M., & Kellogg, M. 1998, ApJ, in press.
Governato, F., Baugh, C. M., Frenk, C. S., Lacey, C. G., Quinn, T., & Stadel, J. 1998, preprint
Kauffman, G. 1998, this volume.
Le Fèvre, O., Hudon, D., Lilly, S. J., Crampton, D., Hammer, F., & Tresse, L. 1996, ApJ, 461, 534
Madau, P. 1995, ApJ, 441, 18
Madau, P., Ferguson, H. C., Dickinson, M., Giavalisco, M., Steidel, C. C., & Fruchter, A. 1996, MNRAS, 283, 1388
Oke, J. B., Cohen, J. G., Carr, M., Cromer, J., Dingizian, A., Harris, F. H., Labrecque, S., Lucinio, R., Schaal, W., Epps, H., & Miller, J. 1995, PASP, 107, 375
Pettini, M. et al. 1998, ApJ, submitted
Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., Pettini, M., & Kellogg, M. 1998, ApJ, in press [astro-ph/9708125]
Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger K. L. 1996, ApJ, 462, L17
Steidel, C. C., Pettini, M., & Hamilton, D. 1995, AJ, 110, 2519
Steidel, C. C., & Hamilton, D. 1993, AJ105, 2017
Wechsler, R. H, Gross, M. A. K., Primack, J. R., Blumenthal, G. R., & Dekel, A. 1997, preprint [astro-ph/9712141]