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A Progress Report on the Caltech Deep Redshift Survey

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Abstract. The Caltech Deep Redshift Survey (CDRS) has been working in two fields. More than 1000 redshifts for faint field galaxies in these two fields are in hand. Our discovery of strong redshift clustering at high z is now amply confirmed by the large data set in hand. Many redshift peaks, with a typical, but non-periodic, spacing of $\approx$100 h^{-1} Mpc, are seen in the HDF data.

We have carried out a preliminary determination of the luminosity function for galaxies, as well as an analysis of the star formation rate as a function of time.

The two point correlation function for galaxies has also been derived. The spatial analysis is directly calculated using the statistics of pairs. A byproduct of this analysis is the measurement of the deviation from smooth Hubble flow ($\approx$300 km/sec in the rest frame) at $z \approx 0.6$.

The spectral analysis is in a very preliminary state. Thus far we have established that the emission line ratios for our sample indicate photoionization by starlight and do not provide any evidence for a contribution by a harder ionizing flux (i.e. AGNs).

1. The Current Dataset for the Caltech Deep Redshift Survey

The CDRS team is headed by J.Cohen and R.Blandford and also includes graduate students David Hogg and Mike Pahre. We are focusing our efforts in two fields, the Hubble Deep Field and the Caltech 0 Hour Deep Field. The choice of the former, given the superb deep imaging by HST (Williams et al 1996), is obvious.

Our redshift survey in the HDF focuses on a field 8 arc-min in diameter. Our sample selection strategy, as described in Cohen (1998), is to attempt to observe every object with $R < 24.3$ mag in the HDF itself and every object with $R < 23.3$ mag in the flanking fields within this area. At present we have redshifts for 512 objects in this field, including 126 objects within the HDF itself. All of these spectra were taken with the Low Resolution Imaging Spectrograph (Oke et al 1995) at the Keck Observatory using multi-slits. Most of these redshifts were determined by me, although in 1996 I coordinated a campaign among the

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[1] Based in large part on observations obtained at the W.M. Keck Observatory, which is operated jointly by the California Institute of Technology and the University of California.

3 major groups using the LRIS spectrograph at the Keck Observatory with the goal of avoiding duplication in our observing efforts. The Caltech and Hawaii groups joined together (see Cohen et al 1996b), while the Lick group's redshifts are in Lowenthal et al (1997) and Phillips et al (1997). Steidel et al (1996) have also published redshifts for several high z objects in the HDF.

The Caltech 0 Hour Deep Field was selected before the HDF was defined. It was, at the time that it was chosen, the field with the deepest WFPC images available in the HST archive and is part of the HST/Medium Deep Survey (Griffiths et al 1994). The selection here is magnitude limited at 2.2μ (K), specifically $K < 20$ mag in a 3 arc-sec diameter aperture in a field 7.3 x 2.0 arc-min^2 in which there are a total of 195 objects in the K-selected sample. At present about 160 of them have redshifts.

Photometry (either ground or space based) over the full optical range from U to I as well as at 2.2μ exists for the entire area of each of the two main fields (Hogg et al 1997, Pahre et al 1997). Objects in each of the two main fields are observed strictly on the basis of magnitude cutoffs irrespective of morphology.

2. Scientific Results Thus Far

2.1. Clustering In Redshift Space

Our major scientific thrust thus far with the sample has been to study the clustering properties in our two fields (Cohen et al 1996 a,b). In both cases we have found much stronger clustering in redshift space than expected. The galaxies over the entire spatial area of each field are concentrated in many strong peaks in redshift space. There is no question now given the large samples in hand that this result is statistically valid.

Figure 1 shows the current redshift histogram for the HDF sample, restricted to the range $0 < z < 1.2$. One may argue as to the origin of these structures in redshift space and how they map into structures in physical space. One possibility is that we are seeing clusters of galaxies, since our field is only $\approx 2\ h^{-1}$ Mpc in the longer dimension. This appears rather unlikely. Among the lines of reasoning leading to this conclusion are the number density of rich clusters of galaxies in the local universe (Bahcall 1988, for Shectman's 1985 clusters, and Postman et al 1996 for the richer Abell clusters), which is too low compared to the number of strong redshift peaks, the lack of any apparent center in the spatial distribution of the galaxies in the most prominent peaks, and the low velocity dispersions we find for galaxies in the peaks. On this basis we believe the structure we see to be a manifestation at high redshift and in the young universe of the same sort of large scale structure seen locally and best exemplified locally by the Great Wall (de Lapparent, Geller & Huchra, 1986) and the voids around it found in the CFA Survey.

We make no claim to be the first to see such structures beyond the Local Universe. Bellanger & de Lapparent (1995) see in the ESO Survey at somewhat smaller redshifts structure reminiscent of what we see. Landy et al (1996) in the Las Campanas Redshift Survey (Shectman et al 1996), which covers the Local Universe at a depth greater than that of the CFA survey, see structure on scales of ≈ 100 Mpc. LeFèvre et al (1995) see what they describe at "picket fence" structure in the CFRS survey.

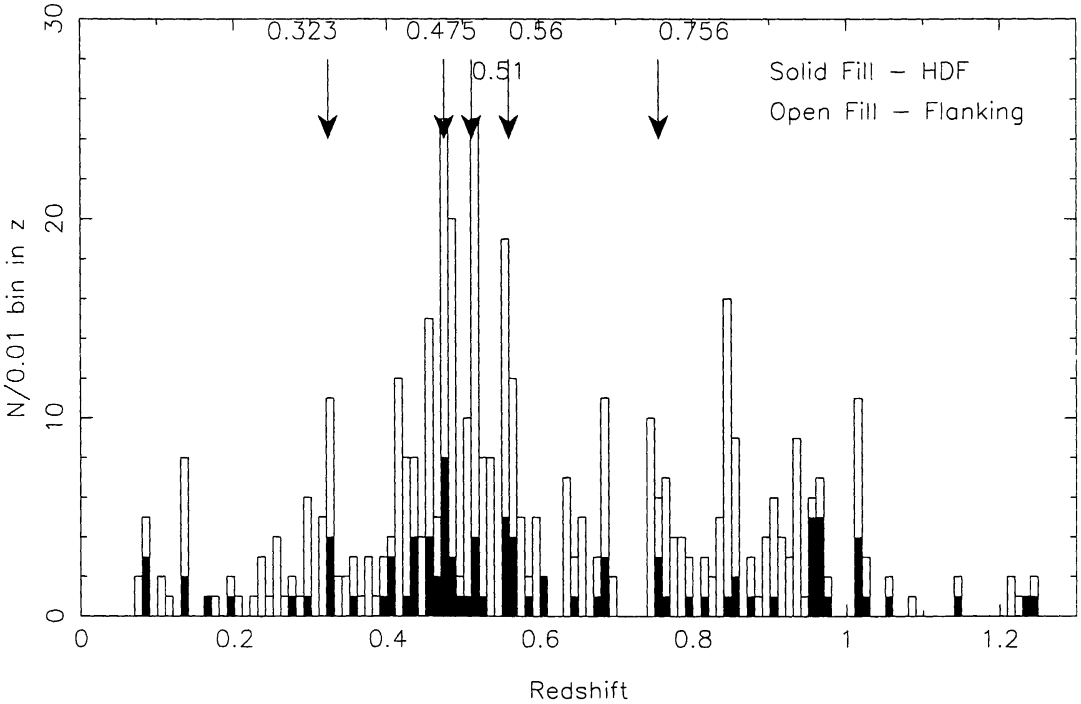

Figure 1. The redshift histogram over the range $0 < z < 1.2$ in the HDF from the combined sample is shown. The solid fill denotes objects in the HDF, while the open fill represents objects in the flanking fields. The arrows denote the five redshift peaks found initially by Cohen *et al.* (1996b).

But in our survey there is more organized redshift structure than in any of these. We believe this to be due to our relatively complete coverage within each field and to the relatively small spatial scale of each field. It is also true that because of our complete sampling we are more affected by the presence of groups of galaxies, and we do see quite a few of these.

The most similar thing seen previously is the structure seen by Broadhurst et al (1990) (see also Szalay et al 1993). Although I don't think the redshifts peaks are as periodic as they claim them to be, there is clearly a characteristic scale, and its near 100 h^{-1} Mpc. Table 1 gives the location in co-moving distance of the stronger redshift peaks we find in the HDF.

2.2. Galaxy Luminosity Function and Star Formation Rates

David Hogg's PhD thesis provides a determination of the luminosity function for galaxies (broken down into several redshift and color bins) from a subset of this data. As shown in figure 2, we agree with the results from the Autofib Redshift Survey (Ellis et al 1996) and from the CFRS (Lilly et al 1995), and find twice as many galaxies per unit volume as are found locally by the APM group (Loveday et al 1992).

The explanation for this problem probably lies in some combination of photometric errors within the APM photographic survey, a possible under density

Table 1. Co-Moving Distances of Strong Redshift Peaks in the HDF

z(peak)	Distance[a] (Mpc)	Separation[a] (Mpc)	z(peak)	Distance[a] (Mpc)	Separation[a] (Mpc)
0.085	320	...	0.687	1839	246
0.133	484	164	0.756	1961	122
0.323	1044	560	0.844	2107	146
0.475	1412	368	0.935	2247	140
0.511	1491	79	1.015	2362	115
0.560	1593	102			

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[a] (H_0 = 75 km/sec/Mpc and $q_0 = 0.5$)

in the local galaxy density, as if we live in or near a void, and/or failure to count low surface brightness galaxies in the local samples. These issues are reviewed by Impey & Bothun (1997).

As already found by several others (Griffiths et al 1994, Cowie et al 1996) little change in the red population is seen out to $z \approx 1$, while there is a hint of strong evolution in the blue population.

After the conference, but before this paper was prepared, Hogg also determined the star formation rate/Mpc^3 as a function of z out to $z \approx 1$ based on the equivalent widths of the [OII] 3727 emission feature. He used the conversion from flux in the 3727 [OII] emission line to star formation rate of Kennicutt (1992). His result appears to be consistent with the rates inferred from the CFRS data and surveys in the HDF compiled by Madau et al (1996).

2.3. Spatial Correlation Function

We have made a rough calculation of the two point galaxy-galaxy correlation function for the the 8 arc-min diameter field of the HDF. This was done directly from a subset of the data by counting pairs, converting the z measurements into a radial coordinate, and combining this with the two tangential coordinates, as is done for local samples. This needs refining before it can be published but the tentative value for r_0 we obtain for $z \approx 0.6$ is 2.1 h^{-1} Mpc, which is in reasonable agreement with the CFRS value given by LeFèvre et al (1996) and appears to be fairly close to the value obtained at somewhat smaller redshifts by the CNOC2 group (Lin 1998). It is, however, considerably smaller than the local value of Marzke et al (1994). The evolution of this parameter with z is discussed from a theoretical point of view by Peacock (1997) among others and the values inferred from the Hawaii Deep LRIS sample by Carlberg et al (1997).

Our method of computing r_0 yields at the same time a measurement for the local deviation from smooth Hubble flow (i.e. the scatter in z for a fixed value of the radial coordinate). That value is at this point poorly determined, but corresponds to about 300 km/sec in the rest frame. It will be extremely interesting to get a more precise value for this parameter.

We also intend in the near future to formulate an analysis that reflects more accurately the tensor nature of the spatial correlation function, along the "walls" as compared to perpendicular to them.

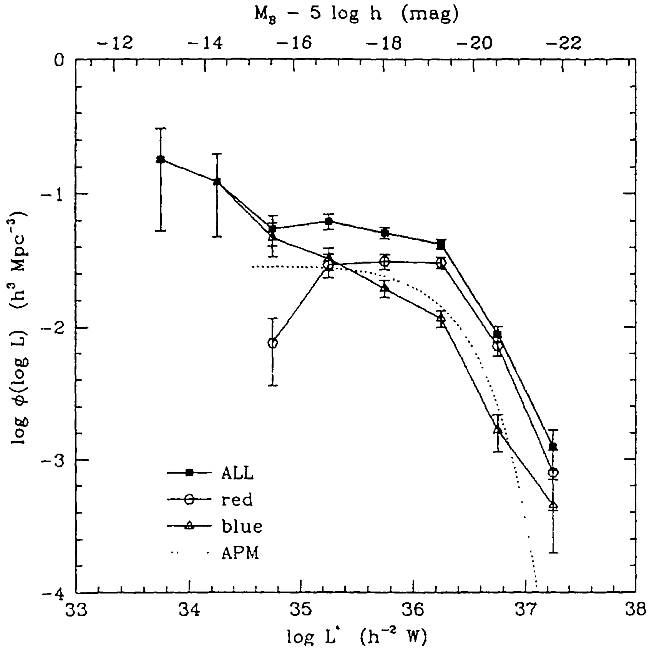

Figure 2. The B-band galaxy luminosity function derived by David Hogg in his thesis from the compiled redshift survey in the HDF as of late summer 1997. The LF is shown for the entire sample (filled squares), and then separately for the red and blue halves (open symbols). The dashed line is that from the Strom-APM group (Loveday *et al.* 1992) over the luminosity range for which it was determined.

2.4. The Outrigger Fields

Since clustering and large scale structure are so prominent in our sample and are of such great interest, we have begun obtaining redshifts for objects in outrigger fields to map the structures on larger spatial scales. An initial set of outrigger fields around the Caltech 0 Hour Deep Field have been observed, yielding several hundred redshifts, but the data is not yet reduced. We are aiming in our first pass for outrigger fields 30 arc-min away from the center of the main field, corresponding to a spatial scale of $\approx 8\ h^{-1}$ Mpc. This is big enough that galaxy clusters are not going to play a role.

We have spectra of 69 galaxies in a field 35 arc-min away from the center of the HDF. Figure 3 shows a comparison of the redshift histogram for the main field and for this outrigger field. There is a powerful suggestion of partial, but incomplete, coherence in redshift structure.

Our major observational effort over the next year or so will be to increase the spatial sampling at large scales using the outrigger fields. We will need to do some modeling and simulations to resolve several issues concerning the strategy of defining and utilizing the outrigger fields to ensure optimal use of our limited observing time.

When this sample is analyzed and enlarged, the study of spatial correlations may best proceed in the future through comparison with numerical simulations. As discussed by several people at this conference, these have now reached the

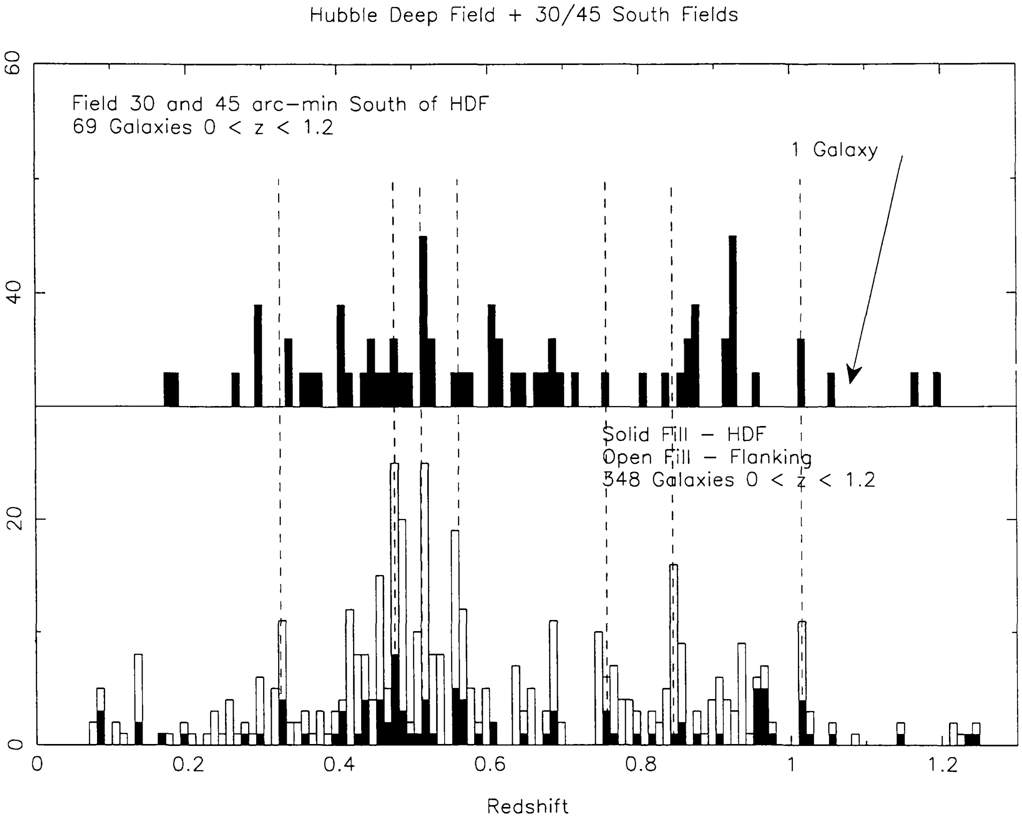

Figure 3. A comparison of the redshift distribution in the HDF with that found for fields 30 and 45 arc-min South of the HDF. The bottom of this figure is identical to figure 1. The top is that of the outrigger fields, with the vertical scale exaggerated as indicated by the arrow. The dashed vertical lines mark the strongest redshift peaks seen in the HDF itself.

level of detail required. Adding in the results for clustering obtained by Steidel et al (1997) at very high redshift will hopefully lead to strong constraints on cosmological models.

With the aid of our very complete redshift survey in the HDF, we are also able to isolate from the ensemble of close pairs a sample of galaxies believed to be genuinely interacting pairs, not just projected neighbors, on the basis of their common redshifts. Subsequent observations of such pairs will be used for for further dynamical studies aimed at understanding and modeling mergers and for determining the masses of galaxies.

2.5. Spectroscopic Analysis and Galaxy-Galaxy Weak Lensing

While the spectroscopic analysis is extremely preliminary at this point, we do have a rough estimate of the fraction of AGNs and QSOs in our database. We have already established in a preliminary fashion that there is no sign of AGNs among the narrow emission line objects, although others claim there is. Tresse et al (1996) find, for example, that with no correction for underlying stellar absorption about 20% of the emission line galaxies in the CFRS with $z < 0.3$ show evidence for a harder ionization source than normal starlight from hot stars. A classical Osterbrock diagram of the ratio of the line strengths of 5007 [OIII]/H_β and 6584 [NII]/H_α of emission line ratios for galaxies from our survey indicates that the ionization is by starlight. The galaxies range out to $z \approx 0.6$ with a median of $z \approx 0.3$. No correction for reddening nor for underlying stellar absorption in the Balmer lines has been applied. A bigger sample of emission line galaxies is needed; it is already in hand, but not yet analyzed in detail. I have also made a first try at determining O abundances using the only unique predictor among the "poor-man's" cases analyzed by Edmunds & Pagel (1984). High (almost solar) O abundances are seen even at $z \approx 0.5$.

A galaxy-galaxy weak lensing analysis for the HDF using the existing redshift sample from our survey has been completed and shows a signal at the $\sim 4\sigma$ level requiring a broad distribution in redshift for the source galaxies (Blandford et al 1998).

3. Concluding Remarks

We have a large sample of high signal-to-noise and high dispersion (for faint field galaxies) spectra. We expect this sample to grow significantly in the next two years. Our ability to analyze this dataset is severely compromised by lack of manpower and lack of funds. We are moving forward as fast as we can.

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