Clustering of Very Red Galaxies in the Las Campanas IR Survey

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Abstract. We report results from the first 1000 square arc-minutes of the Las Campanas IR survey. We have imaged 1 square degree of high latitude sky in six distinct fields to a 5\(\sigma\) H-band depth of 20.5 (Vega). Optical imaging in the V,R,I, and \textit{z'} bands allow us to select color subsets and photometric-redshift-defined shells. We show that the angular clustering of faint red galaxies (18 < \(H< 20.5\), \(I - H > 3\)) is an order of magnitude stronger than that of the complete H-selected field sample. We employ three approaches to estimate \(n(z)\) in order to invert \(w(\theta)\) to derive \(r_0\). We find that our \(n(z)\) is well described by a Gaussian with \(< z >= 1.2, \sigma(z) = 0.15\). From this we derive a value for \(r_0\) of 7\(h^{-1}\)Mpc at \(< z >= 1.2\). This is a factor of \(\sim 2\) larger than the clustering length for Lyman break galaxies and is similar to the expectation for early type galaxies at this epoch.

1 The Las Campanas IR Survey

The LCIR survey was designed to measure the spatial clustering of early type galaxies at redshifts beyond 1 (Marzke et al. 1999; McCarthy et al. 1999). The motivations for this are numerous: clustering provides a means to test competing variants of CDM and galaxy formation scenarios, it provides a path towards matching low and high redshift galaxy populations and it provides an indirect measure of the merging rate, a key part of the galaxy assembly process. The near-IR is the appropriate window on massive evolved galaxies at large and intermediate redshifts. The red giant-dominated spectral energy distributions of evolved galaxies when redshifted to \(z \sim 1\) provide a distinctive spectral signature against the rich foreground of faint blue galaxies. We used a variety of approaches to modeling the colors of luminosities of the early type population in order to define the parameters of our survey. Seeking to ensure a clean 5\(\sigma\) detection of clustering in the 1 < \(z < 2\) range we chose a filter set consisting of V,R,I,\textit{z'},J and \(K_s\) and a survey area of 1 square degree. To comfortably reach \(K_s\) at \(z = 2\) requires a depth beyond \(K_s = 20.5\), a quite ambitious depth for a large area survey. In the present contribution we
describe a “pilot” survey based on H-band observations to a 5σ limit of 20.5 with complementary optical imaging over one square degree.

The near-IR observations for this survey were made with the Cambridge Infrared Survey Instrument (CIRSI; Beckett et al. 1999). This camera is built around a $2 \times 2$ array of Rockwell Hawaii I $1024 \times 1024$ HgCdTe detectors. The detectors are spaced by 90% of a chip dimension in a checker-board pattern. Filled mosaic images are built up by offsetting the telescope in four positions, covering the gaps between the detectors. At the Cassegrain focus of the du Pont 2.5m telescope the size of a filled mosaic, the basic unit of our survey, is $13' \times 13'$. To achieve our present depth of $H=20.5\,5\sigma$ over the full square degree required 100,000 fully calibrated and processed $1024 \times 1024$ H-band frames.

Our survey is spread over six fields at high galactic latitudes. This allows for year-round observing and reduces sample variance effects in the clustering measurements. The fields are listed in Table one and there is considerable overlap with a number of deep fields under discussion at this workshop. This was intentional as our program is dependent on photometric redshifts and we wanted to be in fields where there were abundant spectroscopic redshifts for use as calibrators. The tabulated areas are in square arc-minutes and the depths are $5\sigma$ on the Vega scale.

| Table 1. LCIR Survey Fields |
|----------------------------|
| Field | $\alpha$ | $\delta$ | $b$ | Area | $H$ Depth |
|-------|--------|--------|----|-----|----------|
| HDFS  | 22 33  | -60    | 49 | 1100 | 20.6     |
| NTT Deep | 12 05  | -07    | 52 | 670  | 20.8     |
| CDFS  | 03 32  | -27    | 54 | 670  | 20.5     |
| NOAO S | 02 10  | -04    | 60 | 670  | 20.5     |
| SA22  | 22 00  | +00    | 40 | 670  | 20.5     |
| IoA1511 | 15 24  | +00    | 44 | 670  | 20.5     |

2 Angular Clustering of Red Galaxies

We have assembled photometric catalogs for the first 1000 square arc-minutes of our survey, primarily in the HDFS and NTT $12^h$ fields. From this catalog we have selected color subsets of the data, focusing on the reddest galaxies. In Figure 2 we show our color-magnitude and color-color diagrams for 5200 H-selected galaxies. The color range that we are focusing our analysis on is defined by $I - H > 3$. These very red galaxies are not quite as extreme as the canonical “Extremely Red Objects” (EROs), usually defined by $R - K > 6$,
although our sample will contain all of the EROs within our fields. Selecting
at wavelengths longer than $R$ gives us better sensitivity to early-type systems
at $z \sim 1$ as we are less likely to overlook old populations with low levels of
on-going star formation. The abundance of such systems is demonstrated by
the wide range of $V - I$ colors displayed by our $I - H > 3$ sample (Figure 1).

We have computed the angular correlation function of our red sample.
Our initial analysis in early 2000 was focused on a modest area ($13' \times 39'$) in
the HDFS. We found a very strong clustering signal, 8 to 10 times stronger
than that of the field. This result is very similar to that published by Daddi
et al. (2000) in their 800 square arc-minute survey to $K = 18.8$. Over the past
few months we have increased the size of our catalog of red galaxies ($I - H > 3, H < 20.5$) and in Figure 3 we present the angular clustering measurement
for the first 1000 square arc-minutes of our sample. These data are drawn
from widely spaced fields and so provide a fair sample of structure within our
color and magnitude range. We recover the correct clustering scale for the
complete field population of $\sim 2''$ and again find that the red population is
10 times more strongly clustered than the population as a whole. Our best
fit to $\theta_0$ for this sample is $12''$. Similar to the results reported by Daddi et al.
(2000a,b,) we find that the clustering amplitude is a strong function of the
color. More extreme color-cuts produce larger, but poorly determined, values
for $\theta_0$, brighter magnitude cuts also produce larger clustering amplitudes, but
again the statistics are poor.

Fig. 1. The $I - H$ color magnitude and $V - I$ vs. $I - H$ color-color diagrams for
5200 H selected objects in the first 1000 square arc-minutes of the LCIR survey.
Our $I - H > 3$ color selection threshold is shown with the dashed line.
Fig. 2. The angular correlation function for red galaxies from the Las Campanas IR survey. The lower points are for the full $H < 20.5$ sample, the upper points and curve are for the $I - H > 3$ subsample. The inversion has been done using both the Landy-Szalay and Hamilton algorithms and the errors have been derived from a “Jackknife” analysis of the six sky areas that went into the calculation.

3 The Three Dimensional Clustering Length

The angular clustering scale can be converted into a three dimensional clustering length if one knows the redshift distribution of the sample. We have estimated the $n(z)$ for our sample using three approaches. The first involves modeling the color-magnitude and color-color diagrams for our $H$-selected sample and the red population in particular. Using spectral evolution models with conservative assumptions regarding the amount of passive evolution we infer that the population defined by $I - H > 3, H < 20.5$ is largely confined to the $1 < z < 1.7$ range. A more precise, but not necessarily more accurate, approach involves the use of photometric redshifts. We find that the galaxies with $I - H > 3$ are confined to the redshift range $1 < z < 1.5$. Lastly, we compare directly to the small area deep redshift survey carried out by Cohen et al. (1999). Applying similar color and magnitude cuts to her data again yields a redshift range from 1 to 1.5. We choose to model the $n(z)$ for our sample as a Gaussian with $<z> = 1.2$ and $\sigma_z = 0.15$. The impact of moving $<z>$ by modest (e.g. $\sim 0.2$) amounts on the derived value of $r_0$ is quite small; nearly all of the sensitivity is in the choice of $\sigma_z$. This is intuitive
as a thin redshift shell will produce a larger angular signal for a given 3-D
clustering length than will a broad redshift distribution. The thinness of our
redshift shell can be understood as arising from a combination of our color
cut, which effectively removes the $z < 1$ foreground, and our magnitude limit,
which places us well into the exponential portion of the luminosity function
by $z \sim 1.5$. These effects then give us fairly sharp upper and lower redshift
cutoffs, sharper than one would infer from simple pure luminosity evolution
models of the color-magnitude distribution.

The value for $r_0$ that we derive is $7.7^{+2.1}_{-1.3}$ $h^{-1}$ co-moving Mpc. This is roughly
twice that of the Lyman break galaxies (Giavalisco, these proceedings) and
is not much changed from that of early type galaxies today. Our measured
value for $r_0$ is also quite close to that expected from hierarchical models
for the formation of early type galaxies at early epochs (e.g. Kauffman et
al. 1999). The implications of this large clustering signal are not entirely
clear and should be approached with some caution. We know from sub-mm
and spectroscopic studies (e.g. Graham and Dey 1997; Cimatti et al. 1998;
Dey et al. 1999) that some fraction of the very red galaxies are dusty star
burst systems. The strong clustering of very red galaxies suggests that this
is a population for which merging is important. Whether that merging has
occurred recently and triggered massive starbursts or is if it more indicative of
the assembly of massive early type galaxies in dense environments is not yet
clear. There are several lines of evidence that suggest that the red population
is dominated by relatively dust free spheroids (e.g. Soifer et al. 1999; Yan
et al. 1999). It seems plausible that the “EROs”, that is the most extreme
objects in terms of colors and magnitudes may contain a significant fraction
of dusty systems, but that the bulk of the red galaxy population with colors
close to those expected from $z \sim 1$ ellipticals are indeed slowly evolving
stellar systems. The evolution of the three dimensional clustering over the
range from $z \sim 3$ to the present offers one means of identifying and tracking
such populations.

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