High-Redshift Clustering in the HDF

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ABSTRACT

This paper addresses the problem of detecting high-redshift clustering in deep photometric surveys. We have used photometric redshifts to select different samples of galaxies in the HDF, in order to study their clustering properties. Errors and biases associated with the photometric redshift techniques have been carefully studied through simulations as a function of the photometric uncertainties, the redshift domain and the galaxy type. A direct comparison between photometric and spectroscopic measures of the redshift was also performed. We have studied the 2-D distribution and clustering of galaxies within the 2.5 \(\lesssim z \lesssim 4.5\) domain, in redshift bins of 0.5, using different techniques such as the Kolmogorov-Smirnov test, the galaxy-galaxy correlation function and the number density counts. Although a clustering signal at small scales is detected in the whole redshift interval, the strongest signal at large scales is found in the redshift bins including \(z \approx 3.4\). For these bins, the clustering length is \(r_0 = 0.16 \pm 0.03 \, h_{50}^{-1} \) Mpc, leading to a present correlation length of \(r_0 = 4.1 \pm 0.8 \, h_{50}^{-1} \) Mpc \( (q_0=0.1) \) assuming linear evolution. An excess appears in the correlation function of chip 2 with respect to the fit, at angular scales from 30” to 45”. This excess could be associated to the main structure detected in this field, which contains \(\sim 20\%\) of the objects identified at \(3.4 \lesssim z \lesssim 3.9\), among which 2 galaxies with spectroscopic \(z \approx 3.4\). Its dimensions are \(3 \, h_{50}^{-1} \) Mpc \( \times 0.5 \, h_{50}^{-1} \) Mpc (comoving coordinates, \(q_0=0.1\)). The galaxies at \(3.4 \lesssim z \lesssim 3.9\) exhibit a SFR of a few solar masses per year typically, but their comoving density is a factor of \(\sim 50\) higher than the population of star-forming galaxies reported by Steidel et al. (1996b). The resulting star formation rate density is at least \(1.1 \times 10^{-2} \, h_{50} M_\odot yr^{-1} Mpc^{-3} \) \( (1.8 \times 10^{-2} \, h_{50} M_\odot yr^{-1} Mpc^{-3}) \) with \(q_0=0.1(0.5)\), slightly higher than the results by Madau et al. (1996) at \(2.5 \lesssim z \lesssim 3.5\), and then incompatible with a global decrease of the star formation in this redshift domain. These results on star formation and clustering are consistent with a hierarchical scenario for galaxy formation.
1. Introduction

The detection and the study of high-redshift clustering is one of the main deals in modern observational cosmology. The clustering parameters observed at very high-redshifts constitute a discriminating test for the different cosmological models, and they can greatly help on constraining the cosmological parameters (e.g. White 1996, Baugh et al. 1997, Moscardini et al. 1997). During the last year, several models of galaxy formation in hierarchical scenarios have been proposed to account for the recently observed properties of the galaxy population (Baugh et al. 1997, Moscardini et al. 1997, Steidel et al. 1998). The emerging picture is that the Lyman-break galaxies observed at $2.5 \lesssim z \lesssim 3.5$ are strongly biased mass tracers, associated with large dark matter halos. Their clustering and star-formation characteristics are well reproduced using CDM models, with a relatively high bias parameter ($b \sim 4$). The brightest galaxies in the sample by Steidel et al. (1996a, 1996b) (hereafter ST96a and ST96b) should be interpreted as the progenitors of the brightest present-day galaxies, preferentially located in clusters or groups of galaxies. In order to constrain the theoretical models, it is crucial to measure the clustering properties (through the correlation length) versus the star formation rate density as a function of the redshift.

The problem for performing such measures comes from the extreme difficulty to identify the very faint population of galaxies and to assign a redshift to each object. Most of the time, galaxies at high redshifts are too faint to be studied spectroscopically, and sometimes even too faint to be identified in optical ground-based images. Despite the difficulty, several evidences for high-redshift clustering have appeared recently, such as the groups or clusters of galaxies reported (increasing in redshift) at $z=2.06$ behind CL0939+47 (Dressler et al. 1993), at $z=2.38$ (Francis et al. 1996), at $z=3.14$ (Le Fèvre et al. 1996) and at $z=3.4$ (Giavalisco, Steidel & Szalay 1994). The first spectroscopic and statistically significant samples of high-redshift galaxies are presently being built (ST96a, ST96b, Steidel et al. 1998). Steidel et al. (1998) have reported the discovery of a large scale structure at $z \sim 3$ based on these data. Waiting for the extensive spectroscopic surveys to come in the near future, photometric redshift techniques provide with a useful tool to extend the present surveys up to the faintest magnitude limits, and for a larger number of galaxies (Connolly et al. 1995, Sawicki, Lin & Yee 1997 (SLY), Subbarao et al. 1996, among others). They have already proved their value on identifying high-redshift galaxies (ST96a,
ST96b) and also on unveiling clusters at moderate redshifts (Pelló et al. 1996, Connolly et al. 1996). Nonetheless, the accuracy on the redshift, in this case, is strongly dependent on the photometric accuracy.

The Hubble Deep Field (Williams et al. 1996) offers the necessary deepness, spatial resolution and photometric accuracy to search for structures, especially at \( z \geq 2 \). Villumsen, Freudling & Da Costa (1997) have studied the angular correlation function for galaxies in the HDF, \( w(\theta) \), and, according to them, the clustering signal can be measured up to \( R=29 \). Their results are consistent with a linear evolution of the clustering, giving a present-day correlation length of \( r_0 \sim 4 \, h^{-1} \) Mpc, the same as observed for IRAS galaxies (Fisher et al. 1994). Besides, they do not detect as expected the effects of the magnification bias. Their results evidence the absolute need for a redshift estimate to conclude about the clustering properties at high-redshift. The situation is better at lower redshift \( (z < 1.5) \), where Cohen et al. (1996) have studied the clustering by means of a large spectroscopic survey on the HDF and the surrounding fields. They found some evidence for clustering in the redshift space, in particular two peaks at redshifts 0.5 and 0.8, but they have been unable to detect any particular spatial structure to which these peaks could be associated.

In this paper we investigate the existence of structures at high-redshift \( (z \geq 2.5) \) in the HDF, using photometric redshift techniques to select the different populations of galaxies. The aim is to access the redshift information for a sample of faint galaxies as large as possible, and to perform a combined study of their clustering versus spectrophotometrical properties as a function of the redshift. A similar technique has been applied to the HDF by other authors aiming to study the properties of the faint population of galaxies (see for instance Sawicki et al. 1997; Lanzetta, Yahil & Fernandez-Soto 1996 (LYF)), and in general a reasonable match was noticed between spectroscopic and photometric redshifts, even at high-redshift.

In §2 we describe the method used to compute photometric redshifts in the HDF. The accuracy of the results and the possible biases are discussed on the basis of simulations, especially at the magnitude levels of the objects expected at high-redshift. A direct comparison between spectroscopic and photometric redshifts for low-z and high-z galaxies is also given. The photometric redshift distribution derived for this field is briefly presented in §3. We also study in this section the detailed 2-D distribution of the selected galaxy samples at high-redshift, and we analyze the reliability of the results using different tests for clustering, including the spatial correlation function. The main photometric characteristics of this population of high-redshift galaxies are highlighted in §4, where we compute the star formation rate density for the strongly clustered population. Finally, we discuss the results in §5, as well as the constraints and implications for cosmological models that can be
derived from them, including the future perspectives of this work. Unless otherwise stated, we use $H_0 = 50\,kms^{-1}\,Mpc^{-1}$ and $q_0 = 0.1$.

2. Photometric redshifts

2.1. The method

The technique used to compute photometric redshifts (hereafter $z_{\text{phot}}$) is a standard $\chi^2$ minimization procedure. The observed spectral energy distribution (SED) of each galaxy, as obtained from its multicolor UBRI photometry, is compared to a set of template spectra. The aim is to find the best matching $z_{\text{phot}}$ which minimizes the $\chi^2$, defined as:

$$\chi^2 = \sum_{i=1}^{N_{\text{filters}}} \left( \frac{F_{O_i} - F_{T_i}^{\text{norm}}}{\sigma(F_i)} \right)^2$$

where $F_{O_i}$, $F_{T_i}^{\text{norm}}$ and $\sigma(F_i)$ are, respectively, the observed and the template fluxes in the i band, and the uncertainty associated to the photometric errors in the same filter. $F_{T_i}^{\text{norm}}$ is normalized to match the observed flux in an arbitrary reference band. The four filters are F300W (U), F450W (B), F606W (R) and F814W (I) (see Williams et al 1996, and the WFPC2 Instrument Handbook 1995, from which the filter responses were taken).

The difference with respect to other similar methods (Gwyn & Hartwick 1996, Sawicki et al. 1997 among others) is the large number of template spectra used here. The new Bruzual & Charlot evolutionary code (GISSEL96, Bruzual & Charlot 1993, 1997) has been used to build 5 different synthetic star formation histories, roughly matching the observed properties of local field galaxies: a pure burst of 0.1 Gyr, a constant star-forming system, and three $\mu$ models ($e$-decaying SFR) with characteristic time-decays chosen to match the sequence of colors for E, Sa and Sc galaxies. For each of these types, we select 51 synthetic spectra corresponding to different relevant ages for the stellar populations, in order to closely follow all the significant changes in the theoretical SEDs.

The template database includes 255 synthetic spectra in total. Nevertheless, the effects of metallicity or ISM (in particular, the presence of dust or emission lines) have not been included. According to our simulations (next section), such effects are of second order compared to the main sources of signal with a spectral resolution of $\sim 1000$ Å: the Lyman dropout and the Balmer or the 4000 Å breaks, which are the most important features in the UBRI spectra of galaxies up to $z \sim 5$.

The photometric catalogue for the whole field was obtained through the SExtractor
package (Bertin & Arnouts 1996). The detection of objects on the different images was made at $2\sigma$ level above the sky background, with a minimum size requirement of 5 contiguous pixels (1 pixel=0.1") above this detection limit. The typical size of the faintest objects detected is 10 to 15 pixels at $1\sigma$. Table 1 summarizes the properties of the catalogue. 1588 objects were detected on the whole field, at least in B, R and I filters, and the total number per chip is the same within the statistical noise. Each multiple object showing several bright regions less than 5 pixels apart (within a $10 \times 10$ pixels window) was considered as a single object, and its magnitudes and colors were obtained through the integration of the fluxes within the whole region. Errors derived from SExtractor are given in Table 2.

2.2. Estimate of errors and biases through simulations

We have studied through simulations the accuracy of $z_{\text{phot}}$ as a function of the relevant parameters, namely the photometric errors, the filter bands available and the galaxy type. For each test galaxy, the difference between the $z_{\text{phot}}$ and the model $z$ has been computed, as well as an estimate of the individual uncertainty, $\Delta z$, defined as:

$$\Delta z = 0.5 \times \left[ z(+75\%) - z(-75\% ) \right]$$ (2)

where $z(+75\%)$ and $z(-75\%)$ are the $z_{\text{phot}}$ limits to a 75% confidence level derived from the $\chi^2$ value. Different sets of simulated catalogues were created for this exercise through the GISEL96 library, with galaxies distributed in redshift between 0 and 5. Photometric errors were introduced as gaussian noise distributions of fixed FWHM for each HDF filter band, and uncorrelated for different filters. The first catalogue includes 800 galaxies, basically reproducing the photometric properties of two extreme spectrophotometric types of galaxies with solar metallicity, taken at different ages, with and without evolution: E/S0 galaxy (evolving 0.1 Gyr burst, $z_{\text{form}} = 5.3$, aged 15 Gyr at $z=0$, with $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.1$), and a constant star forming system. Additionally, we have produced a second set of catalogues in order to compute the mean accuracy of $z_{\text{phot}}$ as a function of the photometric errors only, each one containing $\sim 2000$ galaxies uniformly distributed between $z = 0$ and 5, with randomly assigned types between 1 and 8. These 8 types correspond to the same 5 given above plus 3 additional e-decaying SFRs chosen to match S0, Sb and Sd types.

The results of the whole simulations are summarized in Table 3, where the following information for each simulated set of galaxies is given: the standard deviation of the differences between $z_{\text{phot}}$ and the model $z$ ($\sigma z (z)$), the mean systematic bias ($\Delta z = z(\text{model}) - z_{\text{phot}}$), the mean individual uncertainties at 75 % confidence level, and
the percentage of catastrophic identifications. We exclude the catastrophic identifications \(|z(model) - z_{phot}| \geq 1.0\) when computing these values. The results corresponding to the second catalogue are labeled as "all". The dispersion is weakly dependent on the galaxy type, provided that the evolving population of stars is older than \(\sim 10^7\) yr typically, a limitation arising from the ages of the stellar populations used to build our templates. It is worth noting that no contribution from the ISM of galaxies has been taken into account in these simulations, neither on the template spectra nor in the test SEDs. In particular, the presence of emission lines in real SEDs has to be considered as noise included in the photometric uncertainties (0.1 to 0.2 magnitudes at worst).

The dispersion in the estimate of \(z_{phot}\) is strongly dependent on the photometric uncertainties. There is no significant gain for \(\Delta m \lesssim 0.1\), but the dispersion and the number of multiple solutions with similar weight increases quickly up to \(\Delta m \sim 0.3\), which is probably a limiting value for individual objects, and worse than the estimated errors in the HDF (Table 2). Figure 1 displays the result of these simulations when \(\Delta m = 0.1\). About 85\% of the simulated objects have \(z_{phot}\) determined over 75\% confidence level up to \(\Delta m \sim 0.1\). For this photometric accuracy, the mean number of catastrophic identifications, all types joined together, ranges between 1 and 20 \% typically. Nevertheless, there are 2 redshift domains with a poorly determined \(z_{phot}\). The first one is the \(z \lesssim 0.4\), with about 30 \% of catastrophic or multiple identifications when \(\Delta m \geq 0.2\). The deviant objects are among the bluest in our simulations, so a systematic bias exists against these particular SEDs at low redshift. The second one is the \(0.7 \lesssim z \lesssim 1.8\) domain, which is more noisy, as expected because of the lack of strong spectral features going through the filter bands used for the HDF. More precisely, the \(1.4 \lesssim z \lesssim 1.8\) domain has to be avoided because the uncertainties on individual galaxies become huge and the number of degenerate solutions reaches 65 \%. We have performed a reduced number of simulations including the near-IR J and K photometry. The results show as expected that adding the J and K filters allows to solve the degeneracy problem in this particular redshift interval, without improving significantly the accuracy of \(z_{phot}\) outside it.

All the simulated galaxies with \(z \geq 3.4\) are faded in U, with the 912 Å break within the B filter. The results obtained in this particular redshift interval include this effect. It is important to note that all the catastrophic identifications in the \(3.4 \lesssim z \lesssim 4.5\) domain tend to underestimate the population in this interval, without a significant contribution in the opposite sense (low-redshift objects misidentified as high-redshift ones). This effect can be appreciated in figure 1.

We have also computed a specific set of simulations to study the effects of metallicity and reddening on the results, especially at high redshift. For this purpose, a simulated
catalogue was built, containing 1500 objects uniformly distributed between \( z = 0 \) and 5, with randomly assigned metallicities and reddening values. The reddening was taken between 0 and 3 magnitudes in the V rest-frame, according to the SMC extinction curve by Prévot et al. (1984). The results are weakly dependent on the reddening. A more detailed simulation would be required, including a careful modelling of the UV rest-frame SEDs, to discuss the reddening/metallicity biases on the \( z_{\text{phot}} \) in details. This point is out of the scope of the present work. Nevertheless, according to our results in a reduced set of spectroscopic data, neither extinction nor metallicity effects will change the above results significantly.

The dispersion in \( z_{\text{phot}} \) is quite similar to the values found in the literature, even when the techniques used are appreciably different (Brunner et al. 1997, Connolly et al. 1995), but it is hard to compare the accuracy of our \( z_{\text{phot}} \) results as a function of the relevant parameters (photometric errors in particular) to other similar works.

### 2.3. Photometric versus spectroscopic redshifts

#### 2.3.1. Spectroscopic Sample at \( z<1.5 \)

We have computed the \( z_{\text{phot}} \) for a sample of 52 objects observed by the Caltech, Hawaii and Berkeley groups (respectively Cohen et al. 1996, Cowie 1997, Zepf et al. 1996), in order to check the accuracy of \( z_{\text{phot}} \) versus the spectroscopic redshift (\( z_{\text{spec}} \)). The highest redshift in this sample is 1.355, and all the galaxies have been detected in the four UBRI filters. Figure 2 shows the plot of \( z_{\text{phot}} \) versus \( z_{\text{spec}} \) for these objects, where the error bars correspond to \( \pm \sigma_z \), according to the simulations. When comparing the 2 values of the redshift, the standard deviation obtained is \( \sigma = 0.08 \), increasing to \( \sigma \sim 0.15 \) towards \( z \sim 1 \), in good agreement with the above simulations. The \( z_{\text{phot}} \) computed remains in general quite close to the observed spectroscopic redshift and no major systematic bias is observed. The average of \( (z_{\text{spec}} - z_{\text{phot}}) \) is 0.05 for the whole sample, a value which is not highly significant because it is smaller than the standard deviation. The maximum difference measured between \( z_{\text{phot}} \) and \( z_{\text{spec}} \) is 0.41, a value which is attained for a particular galaxy at \( z_{\text{spec}} = 1.01 \) but found with a \( z_{\text{phot}} = 0.6 \). We have compared these results to two other similar works by Sawicki et al. (1997) and Cowie et al. (1997). The methods used are different but the statistical behaviours are very similar, even if some results for individual galaxies are in disagreement. The present dispersion is similar to that of Sawicki et al. (1997) using the same sample of galaxies (\( <z_{\text{spec}} - z_{\text{phot}}>=0.05 \) and \( \sigma_{\text{SLY}} = 0.12 \)), despite the fact that these authors claimed that pure GISSEL models cannot be used for this exercise. The \( z_{\text{phot}} \) obtained by Cowie et al. (1997) over-estimates the redshift by 0.03 and their \( \sigma \) is 0.1.
2.3.2. Spectroscopic Sample at z>2.2

We have also compared the $z_{\text{phot}}$ and $z_{\text{spec}}$ values for high-redshift galaxies with secure redshifts in the range $2.2<z<3.5$, taken from ST96a and Lowenthal et al. (1997) (hereafter LW97). This sample is limited to 16 galaxies, most of them completely extinguished in the U band because the Lyman break moves into the B band. For this reason, the photometry is only available in the B, R and I filters. To compute the $z_{\text{phot}}$ for the U-dropouts, we fixed their U magnitude to 29.5, which represents 1σ level over the sky background for the mean isophotal radius of the sample, and with a fixed error of 0.5.

Results are shown in figure 3. The raw distribution shows an averaged scatter of 0.05 ($<z_{\text{spec}} - z_{\text{phot}}>$ = -0.05) and a standard deviation $\sigma$=0.22. Compared to the $z<1.5$ galaxies, the dispersion is twice higher, but noticeably lower than the previous published values ($\sigma_{\text{SLY}} = 0.28$, $\sigma_{\text{LYF}} = 0.4$). Removing from our sample a galaxy which is extremely discordant, with a $\Delta z$=1.14, the standard deviation reduces to $\sigma$=0.13, surprisingly close to the value expected from the above simulations. We are then confident that in this redshift range $z_{\text{phot}}$ is a fair estimator of the redshift.

3. Results

3.1. Redshift Distribution of galaxies

Among the population of objects detected at least in the three filters B, R and I, 1209 of them, corresponding to 76% of the total sample, have a $z_{\text{phot}}$ value which is well determined above the 75% confidence level. Figure 3 shows the redshift distribution of these galaxies, where ~25% of the sample lies at $z\leq1$ and ~50% is at $z\geq2$. The region of $0.8<z<1.8$ is extremely noisy in our simulations, and the redshift distribution is then less reliable. Two main features appear: one peak at low redshift ($0.4\leq z<0.6$) and a second one at high-redshift ($2.2\leq z<2.6$). The former could be explained as an artifact. According to our simulations, up to ~20-30% of the objects in the $3.6\leq z\leq4$ interval could be misidentified as low-z galaxies with $z\sim0.5$. This happens when the Lyman break is mistaken for the 4000 Å or the Balmer break. On the contrary, the distribution in redshift is extremely reliable at $z_{\text{phot}}>2$, where the contamination by misidentified galaxies is expected to be small. A direct comparison with other similar works is difficult because the method and the selection criteria used are not the same.
3.2. Clustering at z~3.4

We have studied the 2-D distribution of photometrically identified high-redshift galaxies, some of which have been already confirmed spectroscopically by ST96a and LW97. A first approach has been to study each chip individually, except chip 1 (PC) where the detection level is lower. For each chip, we cut the catalogue in redshift slices of 0.5, going from z=2.5 to z=4.5. The thickness of one slice corresponds roughly to the worst dispersion estimated from the simulations. To test whether the samples are consistent with a uniform distribution across the field, a two-dimensional Kolmogorov-Smirnov (hereafter K-S) test (Peacock 1983) has been applied. The results for each chip and redshift slice are summarized in Table 4. It appears that the 2-D distribution of galaxies in the interval [3.5;4] on chip 2 has an extremely low probability, $P_{KS}=0.4\%$, to be drawn from a uniform distribution. This chip contains 2 galaxies already identified at z~3.4 by LW97, plus 2 additional ones tentatively identified at the same redshift. The $z_{\text{phot}}$ of these 2 secure galaxies are $z_{\text{phot}}=3.64^{+0.15}_{-0.05}$ for galaxy A at $z_{\text{spec}}=3.43$ and $z_{\text{phot}}=3.50^{+0.01}_{-0.01}$ for galaxy B at $z_{\text{spec}}=3.368$, the error bars corresponding here to the 90% confidence level. For the 2 tentatively identified at $z_{\text{spec}}=3.35$ and $z_{\text{spec}}=3.37$, we obtained $z_{\text{phot}}=3.56$ and $z_{\text{phot}}=3.57^{+0.15}_{-0.12}$ respectively. All these galaxies are then included in our [3.5;4.0] photometric redshift slice for this chip. The separation between the 2 secure galaxies is only 3", while the 4 galaxies are included in a 40" diameter circle, 0.44 $h_{50}^{-1}$Mpc at z~3.5 ($\sim 2 h_{50}^{-1}$ Mpc for $q_0=0.1$ in comoving coordinates).

If we focus into this redshift interval, and we compute the K-S test for the added catalogue of chips 2 and 3, we find a probability $P_{KS}=0.3\%$. When considering the whole field (chips 2+3+4), the probability for this redshift range remains low, $P_{KS}=0.5\%$. We have also tested a redshift interval centered on z=3.4, with a width of 0.5 as [3.15;3.65], and the result found is $P_{KS}=0.9\%$ for chip 2. It is worth to note that, according to the simulations in §2.3.2, a mean overestimate of the $z_{\text{phot}}$ is expected for objects at $z\geq2.8$. The mean value of this bias is 0.05, but it reaches $\sim 0.1$ at $3.2\leq z \leq 3.6$. For this reason, the strong signal coming from the redshift intervals containing $z=3.5$ is compatible with galaxies being actually at z~3.4.

The K-S test gives 99.96 % confidence on the existence of clustered galaxies at $z_{\text{phot}}=[3.5;4.0]$ on the HDF, but it does not give information about the clustering characteristics of these galaxies. We have examined the correlation length of these galaxies using the estimator of the correlation function $\omega(\theta)$ (eq. [3]) introduced by Landy & Szalay (1993):

$$\omega(\theta) = \frac{DD(\alpha < \theta) - 2DR(\alpha < \theta) + RR(\alpha < \theta)}{RR(\alpha < \theta)}$$ (3)
where for angles $\alpha < \theta$, DD is the number of data pairs, DR is the number of pairs between data and random sample, and RR is the number of random pairs. We proceed by generating a normal random sample, containing 5 times the number of real galaxies, distributed in the same physical area. This operation is repeated for each individual chip. The final $\omega(\theta)$ is an average of the results for 100 different random catalogues. At the same time we measure $\omega(\theta)$ for purely random samples, with the same field size and the same number of objects as the real data, to study the significance of the signal. We will not discuss correlations with lengths less than 10" because our catalogue is biased against such scales. The raw $\omega(\theta)$ results in the redshift interval $[3.5;4.0]$ are summarized in figure 3 for the different chips, and compared to a random distribution. We find a high correlation signal from 10" to 50" for galaxies on chip 2 within the redshift interval $[3.5;4.0]$. When we compare with the other chips in the same redshift interval, only chip 3 shows a signal on smaller scales (from 10" to 20"). For the other redshift intervals considered in the K-S test, no significant signal is found with this estimator on scales larger than 20", in any of the chips when computed individually. These results are consistent with the K-S test.

We have chosen to compute the number density isocontours (Dressler 1980), in order to unveil the structure related to these $z\sim3.4$ galaxies. For this purpose, we have used the whole field catalogue. Results are shown in figure 4. A structure appears on chip 2, about 60" long and 10" wide, which corresponds to $0.66 \, h_{50}^{-1} \, \text{Mpc} \times 0.11 \, h_{50}^{-1} \, \text{Mpc}$ projected at $z=3.4$ for $q_0=0.1$ (around $3 \, h_{50}^{-1} \, \text{Mpc} \times 0.5 \, h_{50}^{-1} \, \text{Mpc}$ in comoving coordinates). It shows a main density peak and two secondary peaks along the structure suggesting substructures merging. It is worth noting that the strongest density peak for this structure is centered only $\sim 10"$ away from the position of galaxies A and B. The position of the structure does not change if we consider only galaxies from chip 2 or from the whole field taken together. We randomly remove some galaxies from our catalogues to test the stability of the position and the shape of the structures. When 10 \% of the points are removed, the position of the large structure in chip 2 remains unchanged, and shows only a lower global intensity. When 25 \% of the objects are removed, the structure is still visible and the position does not change. It is difficult to explain this structure as an artifact due to edge or other spurious effects. We can also see other structures appearing on chip 3, but their scale is smaller ($\sim 20"$), as highlighted by the correlation test, and they are apparently disconnected. Anyway, these structures are less significant because their positions are not stable in front of the random removal of objects.
3.3. Spatial correlation function

The measure of the angular correlation function together with the redshift information gives a direct estimate of the spatial correlation function expressed in proper coordinates (Efstathiou et al. 1991):

\[ \xi(r, z) = \left( \frac{r_0}{r} \right)^\gamma (1 + z)^{-3+\epsilon} \]  

(4)

Assuming small angles, and taking into account the redshift intervals defined by the \( z_{\text{phot}} \), we can deduce from equation (4) the real-space correlation function as the power-law (Peebles 1980, Carlberg et al. 1997),

\[ \omega(r_p) = \frac{\Gamma(1/2)\Gamma((\gamma - 1)/2)}{\Gamma(\gamma/2)} \times r_0^\gamma r_p^{1-\gamma} \]  

(5)

where \( r_p \) is the proper separation of galaxy pairs in the projected direction, expressed in Mpc. We choose first to fix \( \gamma=1.8 \), in order to compare our results to the local population of galaxies. The best power-law fit to the correlation function, with this \( \gamma \) value, gives for the whole field a clustering length of \( r_0 = 0.16 \pm 0.03 \) h\(^{-1}\) Mpc in the \( z_{\text{phot}} \) interval [3.5;4.0]. Considering a linear evolution for the clustering (\( \epsilon=0.8 \)), and a mean redshift of \( z\sim3.65 \) for the population of galaxies, the present correlation length is \( r_0 = 4.1 \pm 0.8 \) h\(^{-1}\) Mpc (see fig. 4). For the other redshift intervals, the mean clustering length is \( r_0 \sim 0.05 \) h\(^{-1}\) Mpc, which gives for the present correlation length \( 0.5 \leq r_0 \leq 2 \) h\(^{-1}\) Mpc. The \( z_{\text{phot}} \) interval [3.0;3.5] is of special interest because it shows the strongest clustering signal after [3.5;4.0]. We obtain a present correlation length of \( r_0 \sim 3 \) h\(^{-1}\) Mpc for this redshift interval when considering the whole field. When we try to fit also the \( \gamma \) value to the different redshift intervals, the best fit is generally found for \( \gamma=1.65\pm0.4 \), but the error-bars are too large to conclude about this parameter.

4. Magnitudes, colors and star-formation rates of the clustered population at high redshift

All the objects with \( z_{\text{phot}} \) observed within the [3.5;4.0] interval are U-dropouts and their redshifts, corrected according to the simulations, actually sample the \( 3.4 \leq z \leq 3.9 \) domain. There are 119 galaxies of this kind on the whole HDF with R magnitudes ranging from 26 to 31, 85 of which are brighter than the completeness limit in magnitude (R\(<29.5 \)). These galaxies represent 13 % of the total HDF population in our catalogue within this apparent
magnitude range. Assuming that this population is uniformly sampling the redshift domain \(3.4 \lesssim z \lesssim 3.9\), their comoving density is at least \(4.1 \times 10^{-3} \, h_{70}^3 \, Mpc^{-3}\) with \(q_0=0.1\) (\(1.8 \times 10^{-2} \, h_{70}^3 \, Mpc^{-3}\) with \(q_0=0.5\)), then a factor of \(\sim 50\) higher than the population of star-forming galaxies reported by ST96b at \(3.0 \lesssim z \lesssim 3.5\), with \(23.5 \leq R \leq 25.0\).

The color-color BRI diagram for the whole HDF distribution is plotted in figure 8. The 119 galaxies belonging to the sample are located in a particular region of this diagram (\(B - R \sim 0.5\) to 0.9, and \(R - I \sim 0.4\) to 0.6). The SEDs of these objects can be fitted by different synthetic stellar populations, and there is a degeneracy at least in the SFR-age-metallicity-extinction space. Nevertheless, when the IMF and the upper mass limit for star-formation are fixed, the allowed parameter space can be roughly constrained. We have used the GISSEL96 code for this exercise, taking into account that these objects are all necessarily dominated by massive stars at the wavelengths seen by the HDF. Two kinds of SFRs were considered: a single stellar population (instantaneous burst), and a continuous star-forming system, both with the Scalo IMF (1986), an upper mass-limit for stars of \(125 M_{\odot}\), and an extinction curve of SMC type given by Prévot et al. (1984). When the burst-model is used, the observed SEDs can be fitted only by a population of stars younger than 0.1 Gyr, with a rest-frame reddening lower than \(A_V \sim 1.6\), and these values are stable in front of metallicity changes. The best fits with a burst-model are obtained with ages ranging from \(10^6\) to \(10^8\) yrs, \(10^7\) yrs and \(A_V \sim 0.6\) being the mean values. When the constant star-forming model is used, the observed SEDs can be fitted with ages ranging from \(10^6\) to \(10^9\) yrs, and \(0.3 < A_V < 0.8\), the best age-\(A_V\) fit being metallicity dependent. For simplicity, only the locations of the solar metallicity models are given in figure 8.

The two galaxies A and B spectroscopically identified at \(z = 3.4\) by LW97 have apparent magnitudes \(R = 27.5\) and \(R = 26.8\) respectively. Galaxy A has a rest-frame 1500 \(\AA\) luminosity of \(L_{1500} = 3.1 \times 10^{40} \, h_{50}^{-2} \, ergs \, s^{-1} \, \AA^{-1}\) with \(q_0=0.1\) (\(L_{1500} = 1.2 \times 1.3 \times 10^{40} \, h_{50}^{-2} \, ergs \, s^{-1} \, \AA^{-1}\) with \(q_0=0.5\)), depending on details of the spectra, as given by the best fit models mentioned above, without any correction for extinction. The mean weighted luminosity over the \(26.0 \lesssim R \lesssim 29.5\) domain, assuming that galaxies are uniformly distributed over the \(3.4 \lesssim z \lesssim 3.9\) interval, is \(L_{1500} = 2.8 \times 10^{40} \, h_{50}^{-2} \, ergs \, s^{-1} \, \AA^{-1}\) with \(q_0=0.1\) (\(L_{1500} = 1.1 \times 1.1 \times 10^{40} \, h_{50}^{-2} \, ergs \, s^{-1} \, \AA^{-1}\) with \(q_0=0.5\)). The weighted averaged SFR obtained for this sample through a continuous star-forming model, without any correction for extinction, is then \(2.6 M_{\odot} \, h_{50}^{-2} \, yr^{-1} (1.0 M_{\odot} \, h_{50}^{-2} \, yr^{-1})\) with \(q_0=0.1\) (0.5). This value is a factor of 10 lower than the mean SFR obtained by ST96b, but the total star formation rate per comoving volume is about 6 times higher, \(1.1 \times 10^{-2} \, h_{50} M_{\odot} \, yr^{-1} \, Mpc^{-3}\) (\(1.8 \times 10^{-2} \, h_{50} M_{\odot} \, yr^{-1} \, Mpc^{-3}\)) with \(q_0=0.1\) (0.5). It is worth to note that this is a lower limit, and that any correction for extinction, according to the best-fit models mentioned above, will tend to increase this value. In particular, taking the maximum reddening allowed to the
continuous star-forming models, which implies a correction of about 1.8 magnitudes to the UV rest-frame sampled in R, we obtain an averaged SFR which is about 5 times higher than the precedent value.

Using the models mentioned above, and assuming that galaxies are uniformly distributed within the $3.4 \lesssim z \lesssim 3.9$ interval, with UV rest-frame apparent magnitudes $26.0 \lesssim R \lesssim 29.5$, we obtain a distribution in absolute magnitude $M_R$ ranging from $-22.4$ to $-17.1$. The mean magnitude of the sample is $R=28.2$, which corresponds to $M_R = -18.7$ to $-20.3$ ($M_B = -18.7$ to $-19.8$), and the widths of the permitted intervals in magnitude are fixed by the different metallicity-age-reddening fits to the models. The mean absolute magnitude is 0.5 to 1.5 magnitudes fainter than the local $M^*$ (Lin et al., 1996), depending on the models and filters, and roughly 10% of the sample is expected to be brighter than $M^*_B$. These values are extremely model dependent, because the wavelength range sampled by the HDF at such high-redshifts is relatively narrow and quite sensitive to short time-scale phenomena, making difficult to fit the observed SEDs by a synthetic stellar population. The near-IR photometry should be useful to constrain the parameter space. According to our modelling, the mean expected colors for this sample are $R - J \sim 1$ and $R - K \sim 2 - 3$. The expected IR magnitudes will be $25.0 \lesssim J \lesssim 28.5$ and $23.0 \lesssim K \lesssim 27.5$, and 15% of the sample ($N \sim 18 - 20$) should be detected with $J \lesssim 26.5$ and $K \lesssim 24.5$.

5. Discussion and Perspectives

We have compared the star formation density computed in §4, in the $3.4 \lesssim z \lesssim 3.9$ interval, to the results on the star formation history by Madau et al. (1996). The data points presented in their figure 9 at high-redshift are lower limits, coming from ST96a at $3.0 \lesssim z \lesssim 3.5$, and from a direct identification of U and B dropouts in the HDF at $2.5 \lesssim z \lesssim 4.5$. Surprisingly, our star formation density in the $3.4 \lesssim z \lesssim 3.9$ interval is similar to their HDF results in the lower adjacent domain $(2.5 \lesssim z \lesssim 3.5)$, and then incompatible with a global decrease of the star formation in this redshift interval. In addition, our integrated star formation rate is a lower limit, not only because of completeness and reddening effects, as mentioned in §4, but also because the simulations of $z_{phot}$ (§2.2) show that the population in this interval can be underestimated (up to $\sim 20\%$ of the faint objects could be lost). Taking into account these effects, except completeness, we find $\log \rho_* = -1.7$ ($M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$) (uncorrected) to $\log \rho_* = -1.0$ ($M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$) (corrected for reddening and $z_{phot}$ systematics), with $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$, the same units and cosmology as in Madau et al. (1996).

About 20% of the total sample detected at $3.4 \lesssim z \lesssim 3.9$ is included within the $3 \sigma$
contour of the main structure detected in chip 2. The evidence for such structures leads to a question: are they the progenitors of the nowadays clusters or groups of galaxies? In a more general way, the problem is to interpret these high-redshift galaxies and their spatial distribution in terms of structure formation. To answer these questions, it is important to compare the present results with the theoretical simulations of galaxy formation and high-redshift clustering. Baugh et al. (1997), using a semi-analytic model for galaxy formation in a hierarchical scenario, have produced a reasonable fit to the star formation data by ST96b and Madau et al. (1996). Their predicted star formation rate density is even in better agreement with the present results (see their Fig. 16). Also, the mean SFRs for galaxies at $z \gtrsim 3$ are expected to be a few solar masses per year, as observed in our sample. Concerning the clustering, these simulations predict a comoving length of $r_0 \sim 4h^{-1}\text{Mpc}$, which reproduces the population of galaxies of ST96b and the present clusters of galaxies, with standard CDM models, a bias parameter $b \sim 4$, and $\Omega_0=1.0$ (model A, $\Lambda_0=0$, $H_0=50$, $b=4.2$) or $\Omega_0=0.3$ (model G, $\Lambda_0=0.7$ and $H_0=60$, $b=3.5$). The present clustering length is also in good agreement with this value, as well as with the typical length for IRAS galaxies (Fisher et al., 1994), and with the clustering at low redshifts (Loveday et al. 1995). It is also fully compatible with the previous correlation length measured by Villumsen et al. (1997). The conclusions are similar when we compare with the high-redshift cluster modelling by Moscardini et al. (1997).

According to the hierarchical scenario, a structure such as the main one detected in chip 2 is probably the progenitor of a group or a cluster of galaxies. Its shape, presenting several substructures, is also what we should expect in a hierarchical model of structure formation (Huss, Jain & Steinmetz 1997). In general, the structures observed at $3.4 \lesssim z \lesssim 3.9$ are expected to be the progenitors of present-day groups or clusters of galaxies. The present results are consistent with a linear evolution regime for the clustering since $z \sim 3.4$, with $\epsilon \sim 0.8$.

An important result is that we observe the strongest clustering on large scales in the $3.4 \lesssim z \lesssim 3.9$ interval, and also a clear signal on similar scales in the $2.9 \lesssim z \lesssim 3.4$ interval ($z_{\text{phot}}$ interval [3.0;3.5]). In both cases, the signal could be associated, at least in part, to a population of galaxies at $z\sim3.4$, the spectroscopic redshift of 2 objects belonging to the main structure. The clustering signal reduces when we consider the population at lower or at higher redshifts, but it is still clearly present at small scales, at least in chips 2 and 3. Taking into account the results by Steidel at al. (1998) in the $2.0 \lesssim z \lesssim 3.4$ interval, the low signal detected in this interval compared to $z\sim3.4$ could be due to an effect of the reduced size of the present field. At $z\gtrsim4.0$, the main problems are the completeness of the sample and the accuracy of $z_{\text{phot}}$, which is dominated by photometric errors when the objects become extremely faint.
We cannot rule out completely that the strong signal detected at $z \sim 3.4$ could be due only to a projection effect on different high-redshift planes. Besides, the combined effect of field size and completeness in the different filters tend to favour the detection of a particular length scale at a given redshift, and then the relative strength of the clustering in the different redshift intervals has to be taken with caution. In any case, we cannot generalize the present results based on a single deep field, and further investigation in other different and deep regions is required to confirm them, combined if possible with an extended spectroscopic survey. Photometry in the near-IR would be useful to improve the modelling of the SEDs and the star formation estimate (see Connolly et al. 1997). But this exercise is difficult with the present ground-based instruments, taking into account the expected magnitudes of the sources (§4) and their typical sizes, which require an excellent spatial resolution. About $10 - 20\%$ of the whole sample should be detected with the NICMOS images of HDF. Concerning the main structure in chip 2, radio observations aiming to detect the Sunyaev-Zel’dovich effect (Sunyaev & Zel’dovich, 1980), along the line of sight of the HDF, could also help to confirm the existence of a massive structure. In a more prospective way, a weak lensing analysis in this field could be greatly improved by the prior knowledge of the mass distribution derived from the light (Bonnet & Mellier 1995, Kaiser et al. 1995, Van Waerbeke et al. 1997), as given by the present study. It could be possible then to estimate the total mass of these structures at high redshift and to constrain $\Omega$.

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Table 1. Photometric properties of the catalogue

| Filter     | completeness magnitude | limiting magnitude | $\mu_\lambda$ (1\(\sigma\), 1 pixel) mag/$^n$2 |
|------------|------------------------|--------------------|-----------------------------------------------|
| U (F300W)  | 28.0                   | 29.5               | 27.00                                         |
| B (F450W)  | 30.0                   | 32.0               | 29.00                                         |
| R (F606W)  | 29.5                   | 32.0               | 29.00                                         |
| I (F814W)  | 29.0                   | 31.0               | 28.50                                         |

Table 2. Mean photometric errors derived through SExtractor

| Filter     | 20-25 | 25-26 | 26-27 | 27-28 | 28-29 | > 29 |
|------------|-------|-------|-------|-------|-------|------|
| U (F300W)  | 0.03  | 0.07  | 0.13  | 0.21  | 0.30  | 0.32 |
| B (F450W)  | 0.003 | 0.01  | 0.02  | 0.05  | 0.10  | 0.23 |
| R (F606W)  | 0.003 | 0.01  | 0.02  | 0.03  | 0.07  | 0.20 |
| I (F814W)  | 0.005 | 0.02  | 0.03  | 0.07  | 0.15  | 0.25 |
Table 3. Dispersion in the photometric redshift as a function of the photometric errors and galaxy types. For each simulated sample, four different informations are given: the standard deviation ($\sigma z(z)$), the mean systematic bias ($\Delta z = z(model) - z_{phot}$), the mean individual uncertainties at 75% confidence level ($\Delta z(75\%)$), and the percentage of catastrophic identifications ($c\%$). See text for more details.

| Galaxy type | $\Delta m$ | 0-0.7 | 0.7-1.8 | 1.8-2.8 | 2.8-3.4 | 3.4-4.5 | 4.5-5.0 |
|-------------|------------|-------|---------|---------|---------|---------|---------|
| E/S0        | $\leq 0.1$ | $\sigma z$ | 0.10 | 0.17 | 0.12 | 0.08 | 0.19 | 0.05 |
|             |            | $\Delta z$ | -0.07 | 0.03 | 0.02 | -0.03 | -0.02 | -0.13 |
|             |            | $\Delta z(75\%)$ | 0.14 | 0.22 | 0.16 | 0.05 | 0.26 | 0.05 |
|             |            | $c\%$ | 4 | 2 | 7 | <1 | 5 | <1 |
| C. SFR      | $\leq 0.1$ | $\sigma z$ | 0.07 | 0.25 | 0.10 | 0.06 | 0.12 | 0.04 |
|             |            | $\Delta z$ | -0.03 | 0.04 | 0.02 | -0.07 | -0.06 | -0.14 |
|             |            | $\Delta z(75\%)$ | 0.15 | 0.36 | 0.17 | 0.04 | 0.24 | 0.06 |
|             |            | $c\%$ | 4 | 10 | 11 | <1 | 11 | 2 |
| all         | $\leq 0.1$ | $\sigma z$ | 0.08 | 0.22 | 0.11 | 0.07 | 0.15 | 0.04 |
|             |            | $\Delta z$ | -0.03 | 0.03 | 0.00 | -0.05 | -0.05 | -0.14 |
|             |            | $\Delta z(75\%)$ | 0.14 | 0.30 | 0.16 | 0.04 | 0.25 | 0.05 |
|             |            | $c\%$ | 4 | 10 | 11 | <1 | 11 | 2 |
| all         | 0.2        | $\sigma z$ | 0.10 | 0.37 | 0.15 | 0.10 | 0.21 | 0.06 |
|             |            | $\Delta z$ | -0.04 | 0.05 | -0.03 | -0.06 | -0.11 | -0.13 |
|             |            | $\Delta z(75\%)$ | 0.27 | 0.56 | 0.31 | 0.11 | 0.33 | 0.09 |
|             |            | $c\%$ | 12 | 12 | 7 | <1 | 38 | <1 |
| all         | 0.3        | $\sigma z$ | 0.23 | 0.44 | 0.20 | 0.17 | 0.24 | 0.09 |
|             |            | $\Delta z$ | -0.07 | 0.08 | -0.03 | -0.03 | -0.14 | -0.13 |
|             |            | $\Delta z(75\%)$ | 0.35 | 0.57 | 0.40 | 0.17 | 0.39 | 0.12 |
|             |            | $c\%$ | 23 | 12 | 11 | <1 | 49 | <1 |
Table 4. Kolmogorov-Smirnov Test Results

| Chip Number | Redshift Interval | No. of Galaxies | $P_{KS}\%$ |
|-------------|-------------------|-----------------|------------|
| 2           | 2.5–3.0           | 53              | 17.0       |
|             | 3.0–3.5           | 47              | 2.5        |
|             | 3.5–4.0           | 43              | 0.4        |
|             | 4.0–4.5           | 25              | 19.0       |
| 3           | 2.5–3.0           | 48              | 3.5        |
|             | 3.0–3.5           | 54              | 6.2        |
|             | 3.5–4.0           | 44              | 3.9        |
|             | 4.0–4.5           | 14              | 20.8       |
| 4           | 2.5–3.0           | 50              | 44.9       |
|             | 3.0–3.5           | 38              | 50.8       |
|             | 3.5–4.0           | 32              | 7.1        |
|             | 4.0–4.5           | 15              | 68.8       |
Fig. 1.— *Top panel:* $z_{\text{phot}}$ vs model redshift ($z(\text{model})$) for all the simulated galaxies with $\Delta m = 0.1$ in all the filters and solar metallicity. *Bottom panel:* $z(\text{model}) - z_{\text{phot}}$ vs $z_{\text{phot}}$ for the same sample, excluding the catastrophic regime with $|z(\text{model}) - z_{\text{phot}}| \geq 1$. 
Fig. 2.— $z_{\text{phot}}$ vs $z_{\text{spec}}$ for the $z<1.5$ sample. Error bars represent $\pm \sigma_z$, the expected uncertainty according to simulations. Dotted and dashed lines correspond to the $\pm 0.08$ and $\pm 0.16$ error intervals, respectively.
Fig. 3.— $z_{\text{phot}}$ vs $z_{\text{spec}}$ for the sample at $z > 2.2$. Error bars represent $\pm \sigma_z$, the expected uncertainty according to simulations. Dotted and dashed lines correspond to the $\pm 0.13$ and $\pm 0.26$ error intervals, respectively.
Fig. 4.— Photometric redshift distribution for galaxies detected at least in B, R and I filters, and with $z_{\text{phot}}$ determined with a confidence level better than 75%.
Fig. 5.— Raw correlation functions from 5" to 100" for galaxies included in the [3.5;4.0] redshift interval. The results for chips 2, 3 and 4 are shown respectively on the up left, up right and bottom left panels. The bottom right panel is the average of 100 random catalogues with the same number of objects than in chip 2.
Fig. 6.— Correlation function for galaxies in the whole field, belonging to the redshift interval [3.5;4.0]. Error bars show the 1 σ Poisson errors. The dashed line is the best power law fit with a fixed $\gamma = 1.8$, and $r_0^2 = 0.039$ (see equation §).
Fig. 7.— Isocontour plot of the projected number density of galaxies compatible with $z \sim 3.4$, superimposed on the I image of HDF field. The first contour represents the mean value over the whole field, with successive contours increasing by $1 \sigma$. The maximum value displayed is $10 \sigma$. The thick line draws the $3 \sigma$ contour of the main structure detected in chip 2. Galaxy A ($z=3.43$) is located at $(233,642)$ and galaxy B ($z=3.37$) is at $(216,644)$. 
Fig. 8.— Color-Color BRI diagram for chip 2. Large squares correspond to the clustered population at $3.4 \lesssim z \lesssim 3.9$, whereas small dots are field objects. All the high-redshift objects are U-dropouts, and their typical error-bars are shown in the top-right corner. The location of the solar metallicity models for the stellar population are also shown. Triangles correspond to the burst model with no-reddening and ages $10^6$, $10^7$ and $10^8$ yrs, increasing redwards. The location of the $A_V = 0.0$, $A_V = 0.8$ and $A_V = 1.6$ burst models (with age $10^6$ yrs) are plotted by circles, increasing redwards. Stars are for the constant star-forming model without reddening, with ages $10^6$, $10^7$, $10^8$ and $10^9$ yrs, also increasing redwards.