Candidate Primeval Galaxies in the Hubble Deep Field

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ABSTRACT

We present the results of colour-selection of candidate high redshift ($2.6 < z < 3.9$) galaxies within the Hubble Deep Field based on the Ly-break at 912 Å. We find 8 such objects in the region, giving a comoving number density comparable to that of nearby bright galaxies (for a flat $q_0=0.5$, $H_0=100$ km s$^{-1}$ Mpc$^{-1}$ universe). We provide basic data on the properties of these objects, and show that despite their absolute magnitude being significantly brighter than $L^*$ (typically $M_B = -22$), they are generally smaller than nearby galaxies. Furthermore, visual inspection of their images shows that they are all highly disturbed systems, with multiple nuclei, tails and plumes, suggesting that they are undergoing merging processes similar to most nearby starburst galaxies. Theoretical models suggest that galaxies form by accumulation of numerous subcomponents, and we suggest that we are seeing this process underway in these objects. It is thus possible that the epoch of galaxy formation might have been discovered.

Key words: galaxies:formation - galaxies:primeval - galaxies:interactions - galaxies:starburst

1 INTRODUCTION

The discovery of very high redshift and primeval galaxies has been a ‘holy-grail’ for cosmologists for many years (Partridge 1974). Amongst numerous approaches to finding forming galaxies and understanding their subsequent evolution, faint imaging surveys, for both number counts (Tyson 1988) and to find individual interesting objects selected by various colour criteria (e.g. multicolour searches for high redshift quasars) are well established techniques (Smith et al. 1994). Among the more interesting results to emerge from these studies has been the discovery, at blue wavelengths,
of many more galaxies than standard ‘no-evolution’ models predict – the so-called ‘faint blue excess’ (Tyson 1988). However, various spectroscopic (Glazebrook et al. (1995a), Lilly et al. (1995)) and HST-based morphological studies (Driver et al. (1995), Glazebrook et al. (1995b)) have shown this excess population to reside at only intermediate redshifts ($z < 1$), and to consist of dwarf late-type spiral/irregular galaxies which undergo substantial luminosity and colour evolution between $z \sim 1$ and the present time. On the other hand, these same studies have shown the redder early-type (E/S0abc) population to have undergone little if any evolution in this period. The formation epoch of these galaxies, therefore, must lie at considerably greater redshift, even if the nature of the faint blue excess has now been determined.

In this context, the Director of the Hubble Space Telescope (HST) assigned a substantial allocation of discretionary time (~ 150 orbits) to a project aimed at obtaining very deep Wide-Field & Planetary Camera 2 (WFPC-2) images of a single ‘random’ field (position 12h 36m 49.4s +62d 12' 58", J2000 (Ferguson et al. 1995); hereafter referred to as the ‘Hubble Deep Field’ (HDF)). Four filters were chosen for these observations, F300W, F450W, F606W and F814W. The data, which were taken over the 13-day period 1995 December 18–30, were made public immediately (Williams et al. 1996) and we present here the results of a programme to search for high redshift counterparts of normal galaxies using the presence of the Lyman break at 912 Å in the F300W filter as an indicator of redshift.

In the next section we describe our selection technique. In section 3 we present our results, while in section 4 we discuss the properties of the objects we find. We draw our conclusions in section 5.

2 SELECTION OF HIGH REDSHIFT OBJECTS

The HDF extends to magnitude limits (on the STMAG system) of 26.7, 28.8, 30.1, and 30.3 in the F300W, F450W, F606W, and F814W filters, respectively, for a 5σ detection in 16 connected 0.04" pixels (Giavalisco et al. 1995). For the present study we wish to detect and then examine the morphological properties of high redshift galaxies. We identify high redshift candidates by looking for a substantial magnitude difference between the F300W and F450W filters. For galaxies with $2.6 < z < 3.9$, the F300W passband will correspond to rest-frame wavelengths shorter than the Lyman cutoff at 912 Å and the F450W filter to longer wavelengths. These high redshift galaxies will thus be undetectable at F300W or will have anomalously red F300W - F450W colours. Objects at still higher redshift will additionally have F450W suppressed.

A similar method has been used successfully by Steidel et al. (1992) to look for companions to high redshift quasars and damped absorption-line systems, and by Guhathakurta et al. (1990) to set a limit on the redshift of the faint-blue-galaxy population. Additionally, the spectral energy distribution of objects at high redshift is likely to be fairly flat redward of the Lyman cutoff (Djorgovski 1992), an assumption that is borne out by recent Keck spectroscopy of $z \sim 3$ galaxies (Steidel et al. 1996). Our selection technique is thus

* STMAG = -2.5log$_{10} f_\lambda - 21.10$ where $f_\lambda$ is the flux in ergs cm$^{-1}$ s$^{-1}$ Å$^{-1}$ received in the bandpass.
to look for all those objects with $F300W - F450W > 2$, and remaining colours ($F450W - F606W$ and $F606W - F814W$) between -0.6 and 0.6. Consideration of the colour-colour diagram in [Steidel et al. 1995] and the detailed photometric modeling of Fukugita et al. [1995] demonstrate that it is very unlikely for lower redshift galaxies of any type to have such colours. Objects not detected in the $F300W$ filter are treated as if they have a magnitude of 27.7, corresponding to the $2\sigma$ upper limit, for the purposes of this selection. We are thus constrained to objects with an $F450W$ magnitude of 25.7 or brighter for our candidates, which usefully guarantees that they will be bright enough for us to study their morphology. Examining the flux zero points for these filters shows that for an $F300W - F450W$ colour $> 2$, the flux ratio between the $F450W$ and $F300W$ bands is $> 6$. This is higher than could be caused by the 4000 Å-break or by absorption in the Ly}$\alpha$ forest where the continuum suppression factor at these redshifts is only about 50% [Storrie-Lombardi 1994].

This selection was based on object catalogs derived from the combined ‘drizzled’ HDF images [Williams et al. 1996] using the automated photometry program SeXtractor written by E. Bertin. A detailed description of the techniques this program employs in the detection and photometry of objects is given by [Bertin 1996]; its specific application to HST WFPC-2 images is discussed by [Smail et al. 1996]. In using it here, SeXtractor was first run on a combined $F606W+F814W$ image to provide a deep ‘master’ list of objects. It was then run on each of the individual $F300W$, $F450W$, $F606W$, and $F814W$ images, the resulting catalogs being matched and merged with the master version. In all cases, a detection threshold of $1.3\sigma$ (where $\sigma$ is the standard deviation of the background noise distribution) and a minimum area after convolution with a 0.3 arcsec top–hat filter of 0.05 arcsec$^2$ (30 connected pixels) were adopted. This resulted in an average of 200, 420, 510, and 420 objects being detected on each WFC chip in $F300W$, $F450W$, $F606W$, and $F814W$, respectively.

SeXtractor computes several different types of magnitude for each detected object but we worked solely with the corrected isophotal (MAG$_{ISOCOR}$) values as they appeared to be the most stable at the faintest limits. This particular magnitude provides an estimate of the total flux from an object by taking the light measured within the threshold isophote and then, by assuming a gaussian profile, making a small (< 5%) correction for the light lost outside this isophote. As a check, these magnitudes were compared with the ‘total’ magnitudes available in catalogs generated at the Space Telescope Science Institute using the FOCAS package [Valdez 1993]. With the exception of the $F300W$ band (see below), excellent agreement was found between the two, both in zero point and scale. The scatter observed between the two sets of magnitudes was also consistent with the random photometric errors expected from photon statistics.

It was noticed that SeXtractor and FOCAS both had difficulties in reliably detecting and measuring objects on the $F300W$ images. A visual inspection revealed that many of the detected objects were spurious and yet a considerable number of real objects were missed. This is undoubtedly due to the problems experienced in flat-fielding the $F300W$ data and removing scattered light. A conspicuous checker-board pattern peculiar to the drizzling scheme was also present around the edges of the frames. These prob-
Problems were dealt with by using the IRAF APPHOT routine to measure aperture magnitudes at each of the positions in our master catalogue, setting the aperture diameter equal to the major axis length computed for each image on the combined F606W+F814W frame. It was these F300W aperture magnitudes that were used in the selection process.

3 RESULTS

Using the above colour and magnitude criteria, we searched our SExtractor catalogue for candidate high redshift objects. We found 9 candidates at $F450W < 25.7$ which satisfied our colour criteria. Visual inspection of all these candidates led us to reject one of these because it lay near the edge of one of the CCD chips and was severely contaminated by spurious flux at the edge of the dithering pattern.

Basic data on the objects is presented in Table 1. Images of the objects are shown in Figure 1a, using the combined F606W+F814W frame. Corresponding F300W images are shown in Figure 1b, demonstrating the lack of any detections, and thus the presumed presence of the Ly break in this band.

We also used a similar search technique to find candidate objects at still higher redshift by looking for a flat F606W -F814W colour combined with $F450W$-$F606W > 2$ and little or no flux in the F300W band. This would select for objects with $3.9<z<5$, though with additional complications from the Ly$\alpha$ forest absorption which becomes stronger. No such objects were found.

Figure 2. Histogram of Absolute Magnitudes. These become 1.4 magnitudes brighter for a $q_0 = 0.05$ universe.

Figure 3. Histogram of Object Sizes. These increase by a factor of 2 for a $q_0 = 0.05$ universe.

4 THE PROPERTIES OF CANDIDATE Z~3 GALAXIES

We found 8 objects on the 3 WFC chips likely to be in the range $2.6<z<3.9$. We now calculate the number-density, absolute magnitude and physical size of these objects; in doing so, we assume them all to be at the mid-point of this redshift range (ie. $z = 3.25$) and adopt an $H_0=100$, $q_0=0.5$ (i.e. Einstein-de-Sitter) cosmology except where stated otherwise.

A total of 8 objects within the 4.7 sq. arcmin area of the HDF gives a surface density for these objects of $1.7$ arcmin$^{-2}$. At matching magnitudes we find a similar surface density of $0.4$ arcmin$^{-2}$ to that of the $R\sim 25.3<z<3.5$...
Figure 1. Images of the Objects. The objects are shown in order from left to right then down the page, starting with 2P1 in the top left and ending with 4P2 in the bottom middle. All images are 4\arcsec square. a Coadded F606W + F814W image. b F300W image showing lack of flux in this band for all objects.
galaxies discussed by Steidel et al. (Steidel et al. 1996). For the assumed redshift and cosmology, the number density of high redshift galaxies in the HDF corresponds to a comoving number density of 0.005 h³ Mpc⁻³ (where $h = H_0/100$); in comparison, nearby bright ($L > L^*$) galaxies have a number density of 0.015 Mpc⁻³ (Parkes et al. 1994). The similarity of these two numbers suggests that we may finally be seeing the progenitors of nearby bright galaxies. The corresponding number for a $q_0 = 0.05$ universe is 0.0009 h³ Mpc⁻³.

Absolute 'blue' magnitudes were determined from the apparent F450W magnitudes using the K-correction calculated by Cowie et al. (1994) for a star-forming ('spiral') galaxy at this redshift. This is based on local galaxy SEDs from Coleman, Wu & Weedman (1980) in the optical, and Mobasher, Ellis & Sharples (1986) in the infrared. We also apply the +0.4 magnitude correction between the F450W and standard B band appropriate for a flat spectrum object using the information provided by Holtzman et al. (1993). These absolute magnitudes must be treated with great caution as neither the applicability of this particular K-correction to our sample of high-redshift candidates nor the required knowledge of the far-UV spectral energy distribution of different present-day types are well determined. Indeed the K correction is similarly large and uncertain for all the filters discussed here since the objects lie at such a high redshift. This notwithstanding, it is of much interest that the values found are at the upper end of the luminosity function of local galaxies† (see Figure 2). In Figure 3 we show the sizes of the major axis of the objects measured at an isophote 3 magnitudes fainter than the peak surface brightness. In contrast to the luminosities, these appear to be significantly lower (median diameter ~4 kpc) than those of their present-day counterparts. A similarly small-sized population of sources was noted by Dressler et al. (1994) in a galaxy cluster found serendipitously on a WFPC-2 image and thought to be associated with a QSO at $z=2.2$.

The object selection is sufficiently bright in the longer wavelength filters that the images are deep enough to allow examination of the morphologies of the selected galaxies. Inspection of the images in Figure 1a immediately demonstrates that all of these objects are disturbed systems, with multiple nuclei, jets, plumes, and asymmetric flux distributions. Indeed, the structures observed are similar to interacting/merging galaxies observed locally e.g. Clements et al. (1996). It has been known for some time that interactions and mergers between galaxies can trigger bursts of star formation (Joseph & Wright 1985). These morphological signatures are also common at intermediate redshifts where HST and other high-resolution observations have revealed objects of this type amongst the blue ‘Butcher-Oemler’ population in clusters (Couch et al. 1994), Dressler et al. (1994)), the faint blue field population (Glazebrook et al. 1995b), and mJy radio sources (Windhorst et al. 1995).

Theoretical models of galaxy formation and evolution (e.g. Kauffman 1995) currently favour the idea that the galaxies we see today were formed as a result of the merging/accretion of a number of subunits. If this is the case then each such accretion event is likely to be accompanied by the vigorous star formation we see in local mergers. The dis-
Table 1. Candidate Primeval Galaxies in the HDF.

| Name | RA(J2000)   | Dec(J2000)   | F450W | F606W | F814W | Abs. B Mag | Size (kpc) |
|------|-------------|--------------|-------|-------|-------|------------|------------|
| 2P1  | 12:36:45.29 | 62:13:47.9   | 25.6  | 25.6  | 26.1  | -21.6      | 4.5        |
| 2P2  | 12:36:53.34 | 62:13:30.4   | 25.3  | 25.1  | 25.4  | -21.9      | 4.2        |
| 2P3  | 12:36:51.97 | 62:14:34.8   | 25.6  | 26.1  | 26.6  | -21.6      | 4.0        |
| 2P4  | 12:36:55.07 | 62:13:49.1   | 25.4  | 25.7  | 26.2  | -21.8      | 3.0        |
| 3P1  | 12:36:49.85 | 62:12:44.6   | 25.4  | 25.9  | 26.5  | -21.8      | 5.0        |
| 3P2  | 12:36:58.20 | 62:12:17.7   | 25.5  | 25.8  | 26.2  | -21.7      | 3.9        |
| 4P1  | 12:36:45.25 | 62:11:54.5   | 23.9  | 24.8  | 24.2  | -23.4      | 10.9       |
| 4P2  | 12:36:41.58 | 62:12:39.9   | 24.5  | 25.0  | 25.4  | -22.7      | 3.1        |

All magnitudes are on the ST magnitude system. No galaxies were detected in the F300W filter, giving a 2 σ magnitude limit \( \gtrsim 27.7 \). Names follow the pattern chip no. P object no, so that the first object detected on chip 2 is 2P1. Absolute magnitudes are calculated assuming a K correction appropriate for spiral galaxies and the appropriate magnitude shift from F450W to B given in [Holtzman et al. 1996]. Values are for \( H_0 = 100 \text{ km s}^{-1} \text{Mpc}^{-1} \) and \( q_0 = 0.5 \). For \( q_0 = 0.05 \), absolute magnitudes get brighter by 1.4 mags, and sizes increase by a factor of 2, while for \( H_0 = 50 \), corresponding figures are 1.5 mags brighter and 2 times bigger.

The effect of viewing these objects in their restframe UV (\( \sim 1670 \text{ Å} \)) is also another factor that must be considered. We might just be seeing the hottest, brightest regions of active star formation in a larger, lower surface brightness structure that we cannot see. Observations of the HDF at IR wavelengths, particularly those conducted with the new NICMOS camera soon to be installed on HST, will be invaluable in addressing the problem of the observed restframe wavelength. For example, the centre of the \( K \) window corresponds, at these redshifts, to \( \sim 5100 \text{ Å} \), conveniently in the restframe optical emission. Observations at these wavelengths from the ground will also be useful in better constraining the spectral nature of these objects; we shall be conducting these in the forthcoming months.

5 CONCLUSIONS

We have presented results on a sample of objects very likely to lie at \( 2.6 < z < 3.9 \). We find that these objects have similar co-moving number density to nearby bright galaxies. However they are significantly more luminous and smaller than nearby galaxies. Almost all of our high redshift objects show signs of a disturbed and multi–component morphology, which we interpret as being due to merging processes taking place during the assembly of a galaxy.

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