Search for Galaxies at \( z > 4 \) from a Deep Multicolor Survey

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Abstract. We present deep BVRI multicolor photometry in the field of the quasar BR1202-07 (\( z_{\text{em}} = 4.694 \)) aimed at selecting field galaxies at \( z > 4 \). We compare the observed colors of the galaxies in the field with those predicted by spectral synthesis models including UV absorption by the intergalactic medium and we define a robust multicolor selection of galaxies at \( z > 4 \). We provide spectroscopic confirmation of the high redshift QSO-companion galaxy (\( z = 4.702 \)) selected by our method. The first estimate of the surface density of galaxies in the redshift interval \( 4 < z < 4.5 \) is obtained for the same field, corresponding to a comoving volume density of \( \sim 10^{-3} \) Mpc\(^{-3} \). This provides a lower limit to the average star formation rate of the order of \( 10^{-2} \) M\(_{\odot}\) yr\(^{-1}\) Mpc\(^{-3} \) at \( z \sim 4.25 \).

1 Introduction

Deep images from the Hubble Space Telescope and ground based telescopes (Keck, NTT, CFHT) are providing new exciting information about abundance and morphology of galaxies in a wide redshift interval up to \( z \sim 4.5 \).

In particular the search of high redshift galaxies is relevant not only to extract information about the physical processes which control the formation of individual objects, but also to probe the cosmological evolution of the formation of galactic structures in the Universe. Indeed cosmological scenarios are attempting to follow the evolution in cosmic time of the galaxy formation, describing in detail the history of the star formation. In the standard CDM cosmology, for example, most of the stars are formed at intermediate redshifts (\( z \sim 1 \); e.g. Cole et al. 1994).

A useful parameter which allows a more direct comparison between theoretical predictions and data interpretations is the star formation rate per unit comoving volume. A reference value at the present epoch of \( \sim 5 \times 10^{-3} \) M\(_{\odot}\) yr\(^{-1}\) Mpc\(^{-3} \) (for a Salpeter IMF) has been recently given by Gallego et al. (1995) on the basis of an H\( \alpha \) galaxy survey.

Recent estimates of the galaxy luminosity function of faint galaxies up to \( z = 1 \) are providing the first evidence of strong evolution by a factor of ten of
the cosmological star formation rate in the redshift interval $z = 0 - 1$ (Lilly et al. 1996; Cowie et al. 1996). This of course implies that more than half of the stars formed at intermediate redshifts, in good agreement with theoretical expectations.

Nevertheless, the same models predict a fraction < 2% of the present mass density in stars at $z > 4$ (Cole et al. 1994). It is therefore at these very high redshifts that cosmological scenarios for galaxy formation are more vulnerable to observational constraints.

Efficient selection criteria are needed to find out galactic structures at these very high redshifts. Well known examples of high $z$ sources are luminous Active Galactic Nuclei like quasars. Their absorption spectra provide unique information on the abundance and ionization state of the intergalactic medium at very high $z$. The presence of the IGM has a twofold cosmological relevance. First, Lyman absorption by the IGM along any line-of-sight produces strong depression of the UV spectrum of high redshift sources. Moreover, its high ionization level requires a large background of UV ionizing photons up to $z \sim 4 - 5$ (Giallongo et al. 1994, 1996). This large UV background is only marginally consistent with that produced by the observed quasars (Haardt & Madau 1996), leaving room for a possible UV contribution by a large number of star-forming galaxies at $z > 4$.

2 The Multicolor Selection

In selecting galaxies which are actively forming stars at very high redshifts, two different approaches can be followed. It is possible to exploit the intrinsic spectral properties expected from star formation activity, or, in case we want to select galaxies at $z > 4$, it is better to exploit the complex but universal opacity to the UV photons of the intergalactic medium.

The selection criteria based on the intrinsic spectral properties exploit the main UV features of the star-forming galaxies like the possible presence of strong emission lines and/or the Lyman absorption break of the flat UV continuum due to the stellar evolutionary properties plus Lyman continuum absorption by the interstellar medium present inside the same galaxy.

Surveys based on the detection of intense Lyman alpha emission by means of narrow band imaging in the optical/IR band in the redshift interval $1.8 < z < 6$ have provided no systematic detections of high $z$ galaxies with only few exceptions (e.g. Macchetto et al. 1993).

A very efficient method based on the detection of the Lyman break present in a flat rest-frame UV continuum has been proposed by Steidel & Hamilton (1992). An appropriate choice of a set of broad band colors can allow the detection of the Lyman break in a given, relatively narrow redshift interval. Steidel used in particular a set of U G R filters adopted to select Lyman break galaxies in the redshift interval $2.8 < z < 3.4$. Since the spectrum of an actively star-forming galaxy is flat longward of the Lyman break, an average color of G–R$\sim 0.5$ is expected in the selected redshift interval. At the same time strong reddening is
expected in the U–G color which samples the drop of the emission shortward of the Lyman break (U–G > 1.5) for z ~ 3 galaxies.

Given the faintness of the galaxies (R ~ 24–25), low resolution spectra with good s/n are being produced only in the last period from observations with the Keck LRIS instrument. Steidel et al. (1996) confirmed with low resolution spectra the identification of 15 galaxy candidates in the expected redshift interval showing the high success rate (> 70%) of this multicolor selection. Extrapolating the success rate obtained for the subsample of their candidates, Steidel et al. (1996) provide a first estimate of the surface density of galaxies at z ~ 3 of the order of 0.4 arcmin$^{-2}$ corresponding to a comoving volume density of 3.6 × 10$^{-4}$ h$_{50}^{3}$ Mpc$^{-3}$. The average rest frame UV luminosity of these galaxies would imply a cosmological star formation rate SFR ~ 3 × 10$^{-3}$ M$_\odot$ yr$^{-1}$ Mpc$^{-3}$.

However, the selection of galaxies at redshift z > 4 becomes considerably more efficient if we take into account the complex absorption produced by the intergalactic medium in the UV spectrum of high z sources. The reddening produced by the IGM in the colors of high z quasars was investigated by Giallongo & Trevese (1990) and a considerable number of very high z quasars has been discovered by means of this multicolor technique (e.g. Warren et al. 1991; Irwin, McMahon & Hazard 1991). Recently, Madau (1995) has refined and applied this multicolor method to the selection of high z star forming galaxies.

![Fig. 1. Spectra of constant star-forming galaxy emitting at z = 3.25 (thin line) and z = 4.25 (thick line) depressed by Lyman absorption by the intergalactic medium. A BVRI filter set (from left to right) has been superimposed (dashed lines).](image-url)

We have plotted in Fig.1 the average IGM absorption affecting the spectral properties of a constant star-forming galaxy emitting at z = 3.25 or z = 4.25. We have adopted the Madau (1995) absorption model and the galaxy spectrum by Bruzual & Charlot (1993) with a Salpeter IMF. First, it is to notice that, at given redshift, the absorption by IGM is characterized by the average Ly-
man alpha forest absorption present just shortward of the galaxy Lyman alpha wavelength and by the absorption of the overall Lyman series down to the Lyman continuum absorption, where the IGM is fully opaque to the UV radiation. While at $z \sim 3$ the Ly$\alpha$ forest absorption produces a fractional decrement of only $\sim 30\%$, at $z \sim 4.5$, 60–70% of the galaxy emission is lost causing a strong and easily detectable reddening in the broad band colors which sample the relevant wavelength interval.

An efficient sampling of this complex absorption requires at least 4 broad band filters. We have chosen the BVI Johnson and Gunn r filters to extend the multicolor selection up to $z \sim 4.5$ (Fontana et al. 1996). These filters are plotted in Fig.1 superimposed to the galaxy spectra.

The r-I color can select the intrinsic flat spectrum of any star-forming galaxy up to $z \sim 4.5$, while the V-r and B-r colors provide evidence of the strong reddening expected because of the Ly$\alpha$ and Lyman continuum IGM absorption, respectively.

To examine how robust is the color selection of $z > 2$ galaxies, we have computed the expected colors as a function of redshift in our photometric system (Fontana et al. 1996) adopting the spectral synthesis Bruzual & Charlot (1993) model. Models of these kind have a number of parameters whose uncertainties can be large in some cases. However, the resulting color changes of a few tenths do not alter the robustness of our color selection, as shown in the following.

To explore how the colors of different galaxy spectral populations are distributed in redshift, we have considered the e-folding star-formation timescale $\tau$ as the main interesting parameter. Different $\tau$ values reproduce different spectral types. For example, a star-formation timescale of $\tau \sim 1$ Gyr is more appropriate for an early type galaxy, while $\tau > 3$ Gyr represent the spectral properties of different late type galaxies. At each “observed” redshift, different ages (i.e. different formation redshifts ranging from 1 to 7) have been considered for galaxies with a given $\tau$. A Salpeter IMF and a solar metallicity have been adopted.

Our relevant colors B-r, V-r, r-I are reproduced as a function of $z$ in Fig.2 only for the case $\tau = 1$ Gyr.

The first remark that should be done is that the r-I color is sampling the intrinsic spectrum of galaxies in a wide redshift interval from $z = 0$ to $z \sim 4.5$. At $z > 4.5$ IGM absorption in the r band produces appreciable reddening in the r-I colors. In selecting galaxies in the redshift range $2.5 < z < 4.2$ the fundamental property of galaxies of all spectral types is the flatness of their rest-frame UV spectra revealed in their r-I colors (see Fig.2). Indeed, in the relevant $z$ interval is always $r-I < 0.2$ due to the intense star formation activity. At $z < 2.5$ the r-I colors are sampling progressively longer rest-frame wavelengths where the galaxy spectra are in general steeper, always resulting in $r-I > 0.2$. Thus, it appears that the r-I color selection is very useful to discriminate high $z$ galaxies in the field. Of course the presence of non-negligible photometric errors suggests the use of bluer colors to select high $z$ galaxies with high confidence.

From Fig.2 it can be seen that the IGM absorption produces strong reddening first in the B-r colors with B-r~1 at $z \sim 3$ then in the V-r color with V-r~1
at $z \sim 4$. Thus, the simultaneous presence of the three colors at the average expected values can select galaxies at $\langle z \rangle \sim 3$ and at $\langle z \rangle \sim 4$ or even more. Any possible contamination by an old population with steep blue spectra (a pronounced 4000 Å break) producing red B-r and V-r colors at $z = 0.5 - 1$ can be avoided just requiring a “flat” r-I color.

**Fig. 2.** Colors as a function of redshift for galaxies with star-formation timescale $\tau = 1$ Gyr. Different formation redshifts have been adopted in the interval $z = 1 - 7$.

### 3 A QSO Companion Galaxy at $z = 4.702$

We have applied this multicolor technique to the field around one of the brightest high $z$ QSO BR1202-07 at $z = 4.694$ (McMahon et al. 1994, Storrie-Lombardi et al. 1996) where at least one very high $z$ galaxy is close to the line of sight to the QSO as shown by the detection of a damped absorption system at $z \sim 4.4$ (Giallongo et al. 1994).

Deep BVrI images were obtained during the 1994 at the NTT with the SUSI direct imaging CCD camera in very good seeing conditions (FWHM~0.5-0.6 for the stellar objects in the r and I images). A diffuse object clearly stands out 2.2 arcsec NW of the QSO with an r magnitude of $r=24.3$. The companion galaxy has the unusual colors expected for star-forming galaxies at $z > 4$, i.e. r-I=0.2, V-r=1.9, B-r>$3$ (Fontana et al. 1996). On the basis of our multicolor selection criterion we estimated a probable redshift range $4.4 < z < 4.7$ depending on the intensity of the galaxy Lyman alpha emission. On the basis of the 1500 Å
continuum flux measured in the I band we derived a star formation rate $\sim 16$ $M_\odot$ yr$^{-1}$ (for a Salpeter IMF). This galaxy has also been detected in the K band by Djorgovski who estimated a magnitude $K \sim 23$. The r-K$-i$ color so derived implies a very young age $< 10^8$ yr independently of details on the assumed metallicity and star-formation timescale.

This galaxy has also been observed in narrow band imaging centered at the Lyman $\alpha$ QSO redshift by Hu et al. (1996) and in imaging spectroscopy by Petitjean et al. (1996). Both authors discovered a Lyman $\alpha$ emission in the galaxy spectrum at $z \sim 4.7$. The strong Ly$\alpha$ emission increases the r flux ($\Delta r \sim -0.8$ mag) keeping a flat r-I color up to $z \simeq 4.7$ despite the strong attenuation in the r band due to the presence of the Ly$\alpha$ forest.

We have recently obtained a low resolution (15 Å) spectrum of this galaxy at the NTT with EMMI (D’Odorico et al. 1996, in preparation) which extends well in the red up to 9000 Å. The spectrum is shown in Fig.3 where the strong Ly$\alpha$ emission is detected at $z = 4.702$ corresponding to a proper distance from the QSO $\sim 600$ kpc or equivalently to a velocity difference $\Delta v \sim 400$ km s$^{-1}$. The line flux $f \simeq 2 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ corresponds to a luminosity $L_{Ly\alpha} \simeq 3.8 \times 10^{43}$ ergs s$^{-1}$. Although this line luminosity could be formally converted into a star-formation rate, some contamination by reprocessing of the QSO UV continuum can not be excluded even at distances $\sim 100$ kpc. More important is the absence of any CIV emission within the flux measured in the I band. This implies that the redshifted I flux can be converted in the star-formation rate of $\sim 16$ $M_\odot$ yr$^{-1}$ previously mentioned.

![Fig. 3. NTT 15 Å spectrum of the QSO-galaxy companion showing a Ly$\alpha$ emission at $z = 4.702$.](image-url)

These observations provide the first evidence of strong star formation activity at $z \gtrsim 4.5$. 
4 A Sample of High Redshift Galaxies

In the 2.2×2.2 arcmin$^2$ field centered on the QSO position we have detected and counted galaxies in the r band down to $r \simeq 26$ mag by means of the SExtractor software package (Bertin 1994). Reliable colors have been obtained for galaxies with $r \leq 25$ mag. We have selected galaxies in two different redshift ranges. First, galaxies satisfying the criterion $r-I < 0.2$ and $B-r > 1$ are expected to lie in the redshift interval $3 \lesssim z \lesssim 4$. We found 11 galaxies at $r \leq 25$ mag in this $z$ interval corresponding to a surface density of 2.3 arcmin$^{-2}$. The derived average comoving volume density at $\langle z \rangle \simeq 3.5$ is $\phi \sim 10^{-3}$ Mpc$^{-3}$. The redshift interval $4 \lesssim z \lesssim 4.5$ has been selected imposing $r-I < 0.4$, $V-r > 1$ and $B-r > 2$. We found 5 galaxies in the field corresponding to a surface density of 1 arcmin$^{-2}$ and to a comoving volume density $\phi \sim 10^{-3}$ Mpc$^{-3}$ at $\langle z \rangle \simeq 4.25$ (see Fig.4).

![Fig. 4 IrVB (from left to right) images of three $z > 4$ galaxy candidates.](image)

Of course these estimates have to be considered as lower limits since galaxies at fainter r magnitudes will contribute somewhat to the volume density. Moreover, the selected galaxies have colors consistent with dust free spectral models. Although an intrinsic reddening $E(B-V) \lesssim 0.1$ does not alter appreciably the r-I color selection, some high $z$ dusty galaxies could be lost by our multicolor selection. The average $\langle I \rangle \sim 24.5$ mag of the galaxies at $3 \lesssim z \lesssim 4.5$ corresponds to an average star-formation rate $\sim 8 M_{\odot}$ yr$^{-1}$. The corresponding cosmological SFR per unit comoving volume is $\sim 10^{-2} M_{\odot}$ yr$^{-1}$ Mpc$^{-3}$ in agreement with the value found by Steidel et al. (1996) at $\langle z \rangle \simeq 3.25$. This limit is about 2 times higher than the present value derived by Gallego et al. (1995) assuming a Salpeter IMF and 5 times lower that at $z \sim 1$ (Lilly et al. 1996). Thus the cosmological SFR increases by a factor of 10 from $z = 0$ to $z = 1$ then it seems to decline by a factor 5 or less up to $z = 4.5$. Assuming a fiducial local stellar mass density $\sim 3 \times 10^8 M_{\odot}$ Mpc$^{-3}$ (Cowie et al. 1995) and an age for the $z > 4$ galaxies of a few $10^8$ yr, a lower limit to the luminous matter density at $z \sim 4.25$
could be of the order of 1% of the local value. Of course our estimates are derived in a small field of 4.8 arcmin$^2$ centered on a high $z$ QSO. Larger areas are needed to reduce density fluctuations.

5 Prospects for the VLT

The large collecting area of the VLT can be exploited to confirm and study high $z$ galaxy candidates selected by multicolor photometry. The first and most obvious follow-up is the spectroscopic observation of galaxies down to $r \sim 25$ mag by means of the mos capability present in FORS. For objects fainter than $r \sim 25.5$, a different approach has to be pursued. Intermediate band filters (200–300 Å) can be used to extend the redshift identification to $r \sim 26.5 – 27$ mag in a reasonable observing time (Fontana et al. 1996, this volume).

6 References

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