HST images in cycle 7 with the NICMOS array.

Some Individual Galaxies

PG 1012+00 ($z = 0.185, M_B = -24.33$). This quasar has two secondary nuclei. There is a spiral (or tidal) arm SE of the system. 25% of the radio emission at 5 GHz is diffuse emission, the remainder is slightly resolved at 0.5 arcsec resolution, and has a steep spectral radio index, so may not be nuclear.

PG 1049–00 ($z = 0.357, M_B = -25.70$). There is some fuzz extending to the north of the nucleus. The extension is also seen in a R-filter image. At most half of the radio emission at 5 GHz is nuclear, with a flat radio spectrum.

PG 1426+01 ($z=0.086, M_B = -23.51$). There is a large asymmetric galaxy under the nucleus and a small secondary nucleus to the SE at 2.5 arcsec (4 kpc) distance. One quarter of the 5 GHz radio emission is diffuse, and the remainder has a steep radio spectrum. As in other sample objects, precise astrometry will tell where exactly the radio emission is located.

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Have We Detected the Primeval Galaxies?

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The identification of the population of primeval galaxies, namely the first galaxies to form stars in the Universe, is essential to provide the much needed observational underpinning to modern theories of galaxy formation and evolution, without which these theories are destined to remain in the realm of speculation. Until recently, and despite decades of intensive search, primeval galaxies had not been identified and thus the epoch (or the epochs!) and the early physics of galaxy formation are still substantially unknown. The combination of ground-based photometry and spectroscopy with the Hubble Space Telescope high angular resolution, is changing this situation and we are now obtaining empirical evidence that a population of galaxies of relatively normal luminosity was already in place at redshifts $z > 3$ and in an evolutionary state characterised by active star formation.

Thanks to telescopes of large apertures and superior image-quality, and to high-efficiency spectrographs, modern deep-galaxy surveys can now obtain redshift identifications for galaxies at about half the age of the Universe, or redshift of about $z \lesssim 1.5$. Combined with the morphological information provided by the exceptional angular resolving power of the Hubble Space Telescope, this is providing a reasonably detailed picture of the evolutionary state of the galaxy population over the latter half of the history of the Universe. A consistent result from the work by several groups (Lilly, 1993; Songaila et al., 1994; Glazebrook et al., 1995a and 1995b; Driver et al., 1995a and 1995b; Steidel, Dickinson & Persson, 1994 and 1995) is that galaxy evolution appears to be strongly dependent on luminosity and morphological type. While the population of bright spirals and ellipticals ($L \sim L^*$, with $L^* = 10^{10}\ L_\odot$) have evolved rather passively from redshifts $z \sim 1$ to the present epoch, the fainter galaxies with luminosity $L \ll L^*$ have undergone a spectacular evolution in morphology, luminosity and number density over the same time span.

The relative lack of evolution in the bright galaxy population suggests that their formation took place at redshifts considerably higher than those probed by the current surveys. Can we observe and track the evolving population of bright galaxies at very high redshifts?

Unfortunately, optical and near-IR spectroscopy of galaxies at redshifts $z > 1.5$ is much harder to obtain due to the limited sensitivity of the current instrumentation and the relative lack of information in the spectral energy distribution which can be probed from the ground. The early primeval galaxy surveys attempted to detect them via their supposedly intense Lyα emission (Partridge and Peebles, 1967; Charlot and Fall, 1993) with optical narrow-band imaging covering the redshift interval $1.8 \leq z \leq 6$. With few exceptions. Noticeably dominated by discoveries made with the ESO 3.6-m and NTT telescopes, including the most distant radio-quiet Lyα galaxy at $z = 3.428$ by Macchetto et al. (1993), no systematic detections of primeval galaxies have been reported with this technique (see Giavalisco, Macchetto & Sparks, 1994 for a review). More recently, these surveys have been extended to near-infrared wavelengths to extend the redshift range up to $z \sim 20$ (Thompson et al., 1994 and 1995; Pahre and Djorgovski, 1995) and/or to include emission lines such as [OII]λ3727, Hβ, [OIII]λλ4969 5007, and Hα, which do not suffer from the severe attenuation by resonant scattering that affects the Lyα line. With a handful of exceptions, no systematic detections have been reported even in this case. We must conclude that either the redshift ranges searched do not correspond to the epoch during which the presumably violent bursts of star formation took place, or that the theoretical expectations of what a primeval galaxy should look like are not realistic (cf. Baron and White, 1987; Charlot and Fall, 1993).

Recently, a more successful technique to detect primeval galaxy candidates at high redshifts has been pioneered by Steidel and Hamilton (1992). This consists of a redshift-tuned colour photometry derived from broad-band imaging

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which exploits the presence of the Lyman discontinuity and the Lymanα forest dimming in the otherwise flat and featureless UV spectra of star-forming galaxies. The method takes advantage of the fact that the observable Lyman discontinuity from high-redshift sources, as well as the Lyα forest dimming, is entirely dominated by the intervening QSO absorption systems and is therefore independent of any assumption about the intrinsic discontinuity, which is a function of the initial mass distribution of the forming stellar population (Madau, 1995). It must be stated, however, that any realistic IMF results in a rather pronounced intrinsic Lyman discontinuity, which is made even stronger by the presence of H I.

A customised filter set, i.e. U_nGR, has been designed to provide the maximum colour information and sensitivity (see Fig. 1). The U_n filter is such that the Lyman continuum break is entirely redward of the U_n passband and blueward of the G band, which in turn has a redward upper-limit at the redshifted Lyα wavelength. The R is a compromise between the Johnson R and I bands so as to provide a sufficiently wide wavelength baseline while at the same time avoiding much of the night-sky brightness, and samples the rest-frame UV at about 1600 Å. In practice, star-forming galaxy candidates with redshifts $z > 3$ are selected from colour-colour plots to have very red $(U_n - G)$ and moderately blue $(G - R)$ colours, respectively. Figure 1 shows the synthetic spectrum of a star-forming galaxy redshifted to $z = 3.4$ and the transmission curves of the U_nGR photometric system. This technique is sensitive in the redshift range $3 \lesssim z \lesssim 3.5$. The lower limit is dictated by the need to make sure that the Lyα break falls out of the U_n band. The upper limit is set by the amount of Lyα forest absorption, which for higher redshifts becomes so severe that the colours of a high-redshift galaxy become indistinguishable from those of the faint galaxy population (placed at much lower redshifts), even if the filters are modified and tuned to follow the redshifting spectrum. We will refer to the candidates selected with the above method as Lyman-Limit Flat Spectrum (LLFS) galaxies.

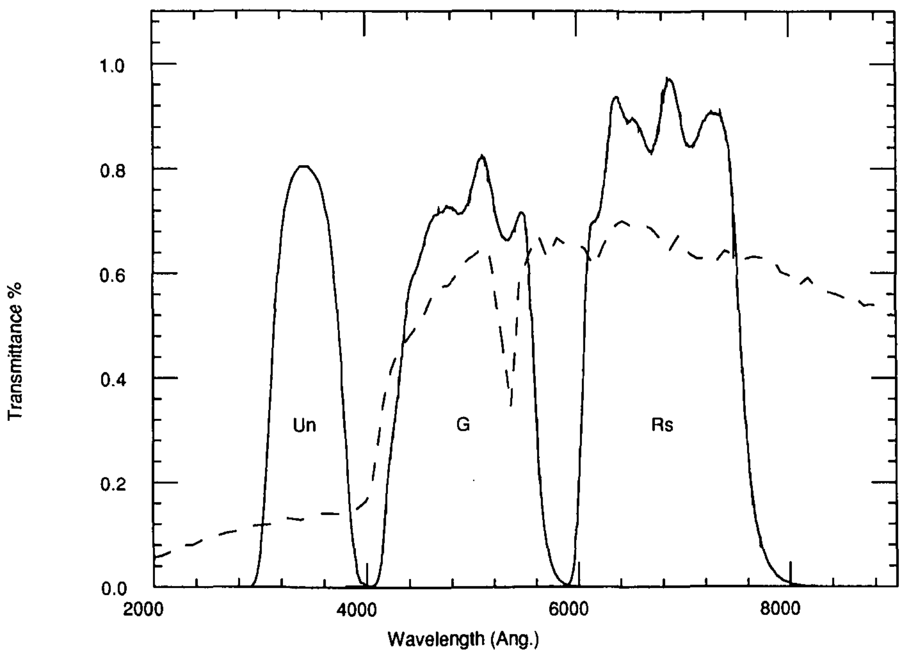

Figure 1: *The idea behind the multicolour selection of galaxy candidates at z > 3. Shown is the synthetic spectrum of a star-forming galaxy (f_ν units in an arbitrary scale) redshifted to z = 3.4 along with the transmission curves of the U_n, G and R passbands. The U_n filter lies entirely blueward of the Lyman discontinuity. The G filter probes the range between the discontinuity and the Lyα line, a region affected by the intervening Lyα forest line-blanketing. Finally, the R filter probes the rest-frame UV continuum redward of the Lyα. Its effective wavelength is intermediate between those of the Johnson R and I passbands so as to provide an improved wavelength baseline, avoiding much of the sky-lines background.*

Is there any empirical evidence for the existence of a population of forming galaxies with $z > 3$? As a result of the early observations by Steidel and Hamilton (1993), a number of LLFS galaxies have been identified in the field towards Q0000-263 (a quasar with $z_{em} = 4.11$), including the candidate damped Lyα/Lyman-limit system of the QSO at $z_{abs} = 3.389$. These LLFS galaxies have apparent magnitudes consistent with those of

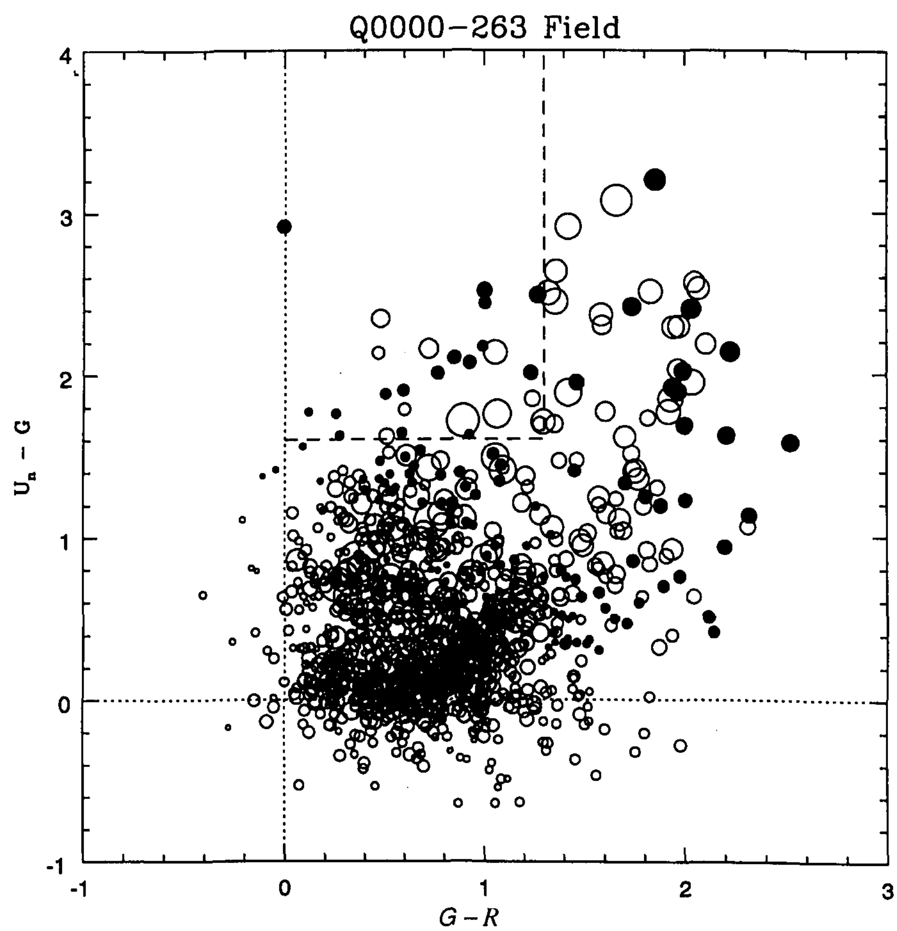

Figure 2: Colour-colour plot U_n–G vs. G–R in AB magnitudes (AB = –2.5 Log(f_ν) – 48.595) obtained with the NTT plus EMMI in the field towards Q0000-263. The vertical and horizontal lines show the locus of flat-spectrum sources, for which the colours are equal to zero in the AB magnitude system. The locus U_n–G > 1.6; G–R < 1.3 defines the region where to expect galaxies with z > 3 (see text). Galaxies in this region have colours rather different from those of the field galaxy population, placed at redshifts z ≪ 3, with a deviation from the centre of the distribution of ≈ 4σ.

normal bright galaxies, that is with luminosity $L \sim L^*$, caught during a star-forming phase with star formation rates of ~ 50–100 $h_{50}^{-1}2$ $M_\odot$ yr^{-1} (with $q_0 = 0$), namely $24 < R_A < 25.5$ or $2 \leq L/4L^* \leq 6$ (assuming an Im spectral type), and are undetected in U_n down to $U_n \sim 27$, with colours $U_n - G > 1.7$ and $G - R < 1.2$. Figure 2 shows a colour-colour plot obtained from our recent NTT U_nGR imaging of the Q0000–263 field (see later). We explicitly note that these colours are *very different* from those of the average field galaxy population. In particular, they show the existence of a *sharp discontinuity* in an otherwise flat (in $f\nu$ units) spectral energy distribution, which is not detected in field galaxies.

Madau (1995) has modelled the effects of the stochastic attenuation produced by intervening QSO absorption systems on the broadband colours of cosmologically distant galaxies. His estimates place the identified LLFS galaxies within the realm of what might be called normal, attenuated star-forming galaxies at redshift $3 < z < 3.5$, and show that, if

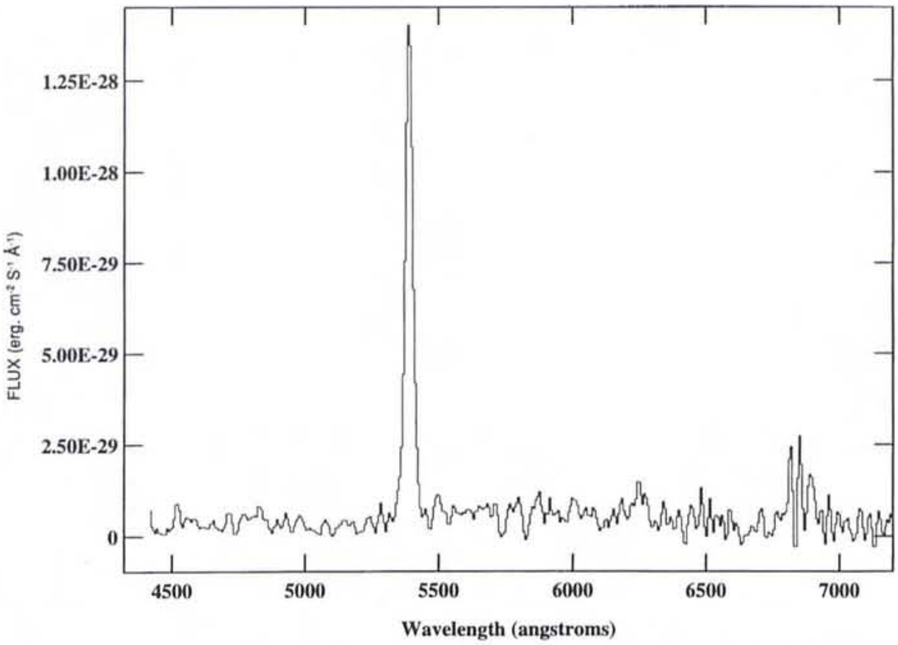

Figure 3: A spectrum of galaxy G2 at z = 3.428 obtained with the 3.6-m telescope plus EFOSC1 and PUMA. The total integration time was 8 hours and the resolution is ~ 19 Å. Clearly visible is the intense Lyα emission with rest-frame equivalent width of ~ 170 Å and the dimming of the continuum shortward of the line due to the intervening Lyα forest blanketing. No other lines are detected in the spectrum.

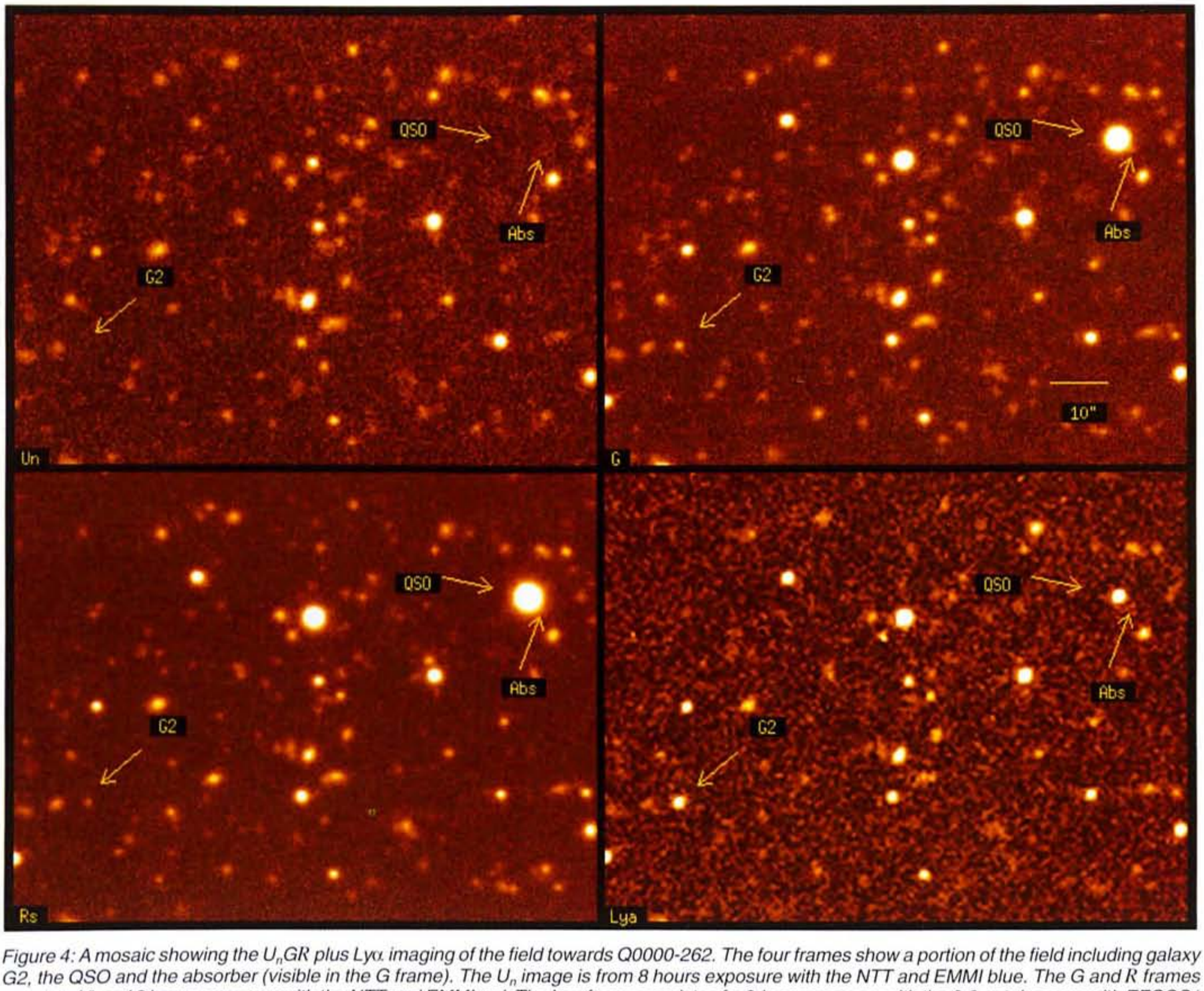

Figure 4: A mosaic showing the U_nGR plus Lyα imaging of the field towards Q0000-262. The four frames show a portion of the field including galaxy G2, the QSO and the absorber (visible in the G frame). The U_n image is from 8 hours exposure with the NTT and EMMI blue. The G and R frames consist of 3 and 2 hours exposure with the NTT and EMMI red. The Lyα frame consists of a 2-hour exposure with the 3.6-m telescope with EFOSC1 and has been obtained with an interferential narrow-band filter (ESO #435). The four frames have been resampled to a common pixel scale of 0.27 arcsec. The seeing of the final stack in each case is about 1.3, 1.1, 1.2 and 1.3 arcsec, respectively.

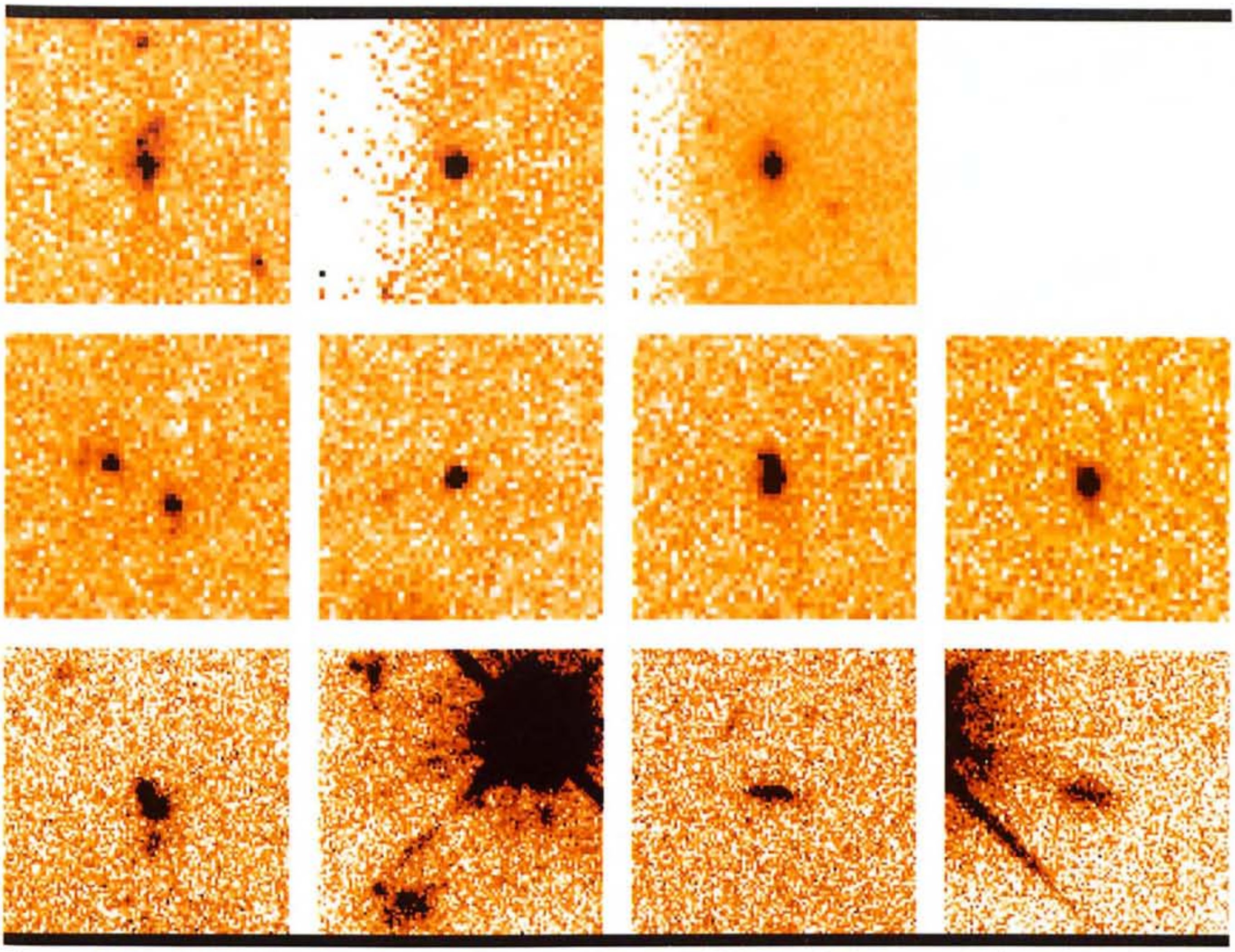

Figure 5: A mosaic of HST images of z > 3 galaxy candidates obtained with the WFPC2 camera. The first two rows are from the Wide Field Camera (scale: 0.1 arcsec/pixel). The last row is from the Planetary Camera (scale: 0.046 arcsec/pixel). All images but the two leftmost in the last row are of the candidate members of the z = 3.4 putative cluster towards the Q0000-263 field, identified by Giavalisco et al. (1994). They have been obtained with the filter F606W (λ = 5940 Å) in 4.3 hours of integration. Galaxy G2, the only spectroscopically confirmed candidate so far, is the third from left in the second row. The QSO and the candidate absorber (z_{abs} = 3.389) are in the bottom rightmost panel. The first two images from left in the bottom row are from the field towards Q0347-383, and have been obtained with the filter F702W (λ = 6870 Å) in 5 hours of integration. The top rightmost image shows a stack of all the WF camera galaxies towards Q0000-263 to show the "average" image of a z > 3 galaxy candidate. This image corresponds to 35 hours of integration. Given the large degree of morphological variety that HST imaging has revealed in faint galaxies of comparable apparent magnitude, the strict similarity of the z > 3 candidates is surprising and reinforces the idea that we have identified a population of galaxies characterised by common properties. The fact then that their "average" image is so similar to an elliptical galaxy (see also Fig. 6) is very remarkable.

dust extinction is present, it is likely to be small.

In an independent project, using the 3.6-m telescope in combination with EFOSC, Macchetto et al. (1993) and Giavalisco et al. (1994b) have spectroscopically confirmed the redshift of one LLFS galaxy in the Q0000–263 field, a Lyα emitting galaxy at $z = 3.428$ (galaxy G2 in the following), previously found by Macchetto et al. (1993) with a different search technique. This is extremely important, because it empirically demonstrates that among LLFS galaxies there are indeed bright, star-forming galaxies at z > 3. Galaxy G2, inconspicuous when observed through broad-band filters longward of U_n ($R_{G2} = 24.2$ or $L_{G2} \approx 6\ L^*$), has a Lyα rest-frame equivalent width of ≈ 170 Å. We show in Figure 3 a spectrum of the galaxy obtained with the 3.6-m telescope and EFOSC (see also Figure 4, bottom right panel).

Although a quantitative assessment of what fraction of LLFS galaxies are actually star-forming galaxies at high redshift will have to wait for systematic spectroscopic observations (or other equivalent methods, see later), two pieces of evidence already support the fact that we have identified a population of high-redshift star-forming galaxies. The first comes from a clustering analysis of the currently identified LLFS galaxies, while the second comes from the HST observations.

Very interestingly, Giavalisco et al. (1994a) showed that the 14 LLFAS galaxies identified towards Q0000–263 are not homogeneously distributed in the observed field, but are clustered around galaxy G2 and the QSO absorber. This implies that those 14 galaxies, whose broad-band spectral energy distribution is *identical* to that of G2 and the absorber, are spatially correlated with them, or, in other words, placed at the same redshift. These 16 galaxies are, therefore, members of a "concentration" (a nascent cluster or supercluster?) at $z \approx 3.4$. This result agrees with the observed strong clustering of Lyα emitters around damped absorbers at very high redshifts (Wolfe, 1993), reinforcing the evidence that clustering characterises the distribution of bright galaxies already at early epochs (incidentally, this suggests that, in general, the fraction of low- or medium-redshift interlopers, which are wrongly classified as LLFS galaxies because of photometric errors, must be small, as there is no reason to expect photometric errors to be spatially correlated). Thus, we have started to obtain fundamental information that will constrain the theories of structure formation in the Universe, and we have found evidence that an entire *population of galaxies*, was in place and *under construction* at $z \approx 3.4$.

Given the importance of the above results, we decided to obtain even more accurate photometry and search for more candidates in the field towards Q0000–263. We manufactured a set of the U_nGR passbands to match the EMMI specifications (both the blue and the red arm), and we have observed the field for a total of three nights in August 1993. Unfortunately, although the nights were photometric, the seeing was not ideal, ranging from 2.2 to 1.0 arcsec, placing serious limitations on the signal-to-noise. Nevertheless, we have improved the previous observations by about 0.5 mag, obtaining the deepest U_nGR frames so far. We show in Figure 4 a portion of the field observed through the U_nGR filters which include galaxy G2, along with a Lyα image of the galaxy obtained with the 3.6-m telescope. Figure 2 shows the $U_n - G$ vs. $G - R$ colour-colour plot. We will observe the Q0000–263 field again, in the fall 1995, with a set two narrow-band filters designed to probe another sharp discontinuity in the SED of the candidate high-redshift galaxies found, namely the discontinuity around the Lyα wavelength. If these galaxies are really at $z > 3$, the new narrow-band observations, together with the broad-band colours derived from the previous observations, will allow us to constrain the redshifts of the galaxies in a very narrow interval around $z = 3.4$. Thus, although we will not actually measure the redshift with the typical spectroscopic precision, we will nevertheless be able to confirm the nature of our candidates and the existence of a cluster of galaxies at this redshift.

The other very important piece of evidence that supports the identification of the LLFS galaxies with a population of young, bright galaxies at high redshift is their morphological similarity. How do the LLFS galaxies look when observed at the high angular resolving power of the Hubble Space Telescope? WFPC observations by Giavalisco et al. (1995) through the F555W filter have shown that the light profile of the core of G2 is characterised by an $r^{1/4}$ law with $r_e \approx 1.3$ kpc, with no evidence of an AGN-like central source, while the outer regions exhibit a rather young morphology with elongated structures possibly emitting Lyα, and low surface brightness nebulosities. This is suggestive of a relatively recent collapse of the core of G2 which has resulted in a young elliptical galaxy or the bulge of a spiral. Thus, G2 appears to be the progenitor of a bright galaxy,

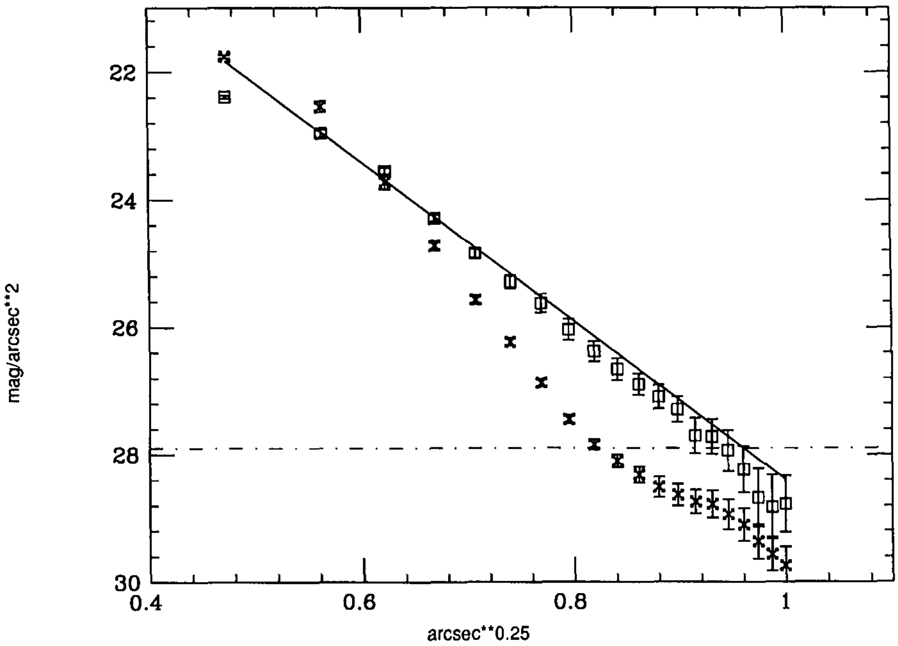

Figure 6: A plot showing the radial light profile of the "average" image of the $z > 3$ galaxy candidates shown in Figure 5, obtained by stacking together 7 galaxies from the Q0000-263 field, including galaxy G2 at $z = 3.428$ (open boxes). The error bars give the 1σ fluctuations along the elliptical isophotes. The crosses show the profile of a star scaled to the same magnitude. The continuous line shows the $r^{1/4}$ law. The dash-dotted line shows the 3σ-level fluctuations of the sky. The data can be modelled by a de-Vaucouleurs law over about 7 mag or 2.8 order of magnitudes.

whose estimated stellar mass at the present epoch would be $M \sim 5^{10}–10^{11}$ $M_\odot$, therefore in the observed range of spirals and moderate luminosity ellipticals.

Recent WFPC2 observations by Giavalisco et al. (1995b, in prep.) of the Q0000–263 and other fields have shown a surprising degree of similarity in the morphology of the LLFS galaxies (Giavalisco and Macchetto, 1995, in prep.). These images show that the large majority of the LLFS galaxies are characterised by a compact, or bulge-like, morphology, in some cases surrounded by diffuse, low surface-brightness nebulosities. A minor fraction shows a diffuse, elongated, or disk-like, morphology. Most noticeably, among this subgroup there is the candidate damped Lyα absorber of QSO 0000–263. Wolfe (1986) has proposed that the damped Lyα absorption systems are indeed caused by protogalactic disks, and our observations seem to confirm this view. All the LLFS galaxies have very similar sizes, namely ≈ 1 arcsec in diameter. We show in Figure 5 a mosaic of WFPC2 images of LLFS galaxies from the Q0000–263 and Q0347–383 fields. The upper right panel of the mosaic shows the "average" image of a LLFS galaxy obtained by stacking together all those with compact morphology. Figure 6 shows the light profile of this image obtained fitting elliptical isophotes to it. The continuous line is the $r^{1/4}$ law, which fits the data over more than 2 orders of magnitudes, showing that LLFS galaxies with compact morphology look, on average, very similar to bulge systems. Given the remarkable variety found with HST in the morphology of galaxies of the same magnitude (but lower redshifts), the extreme similarity of the LLFS galaxies is a rather surprising result, which is now supported on a statistical basis by the relatively high number of these galaxies, observed at high resolution.

In conclusion, our ESO and HST observations have shown the existence of a well-defined class of galaxies, which we have labelled LLFS galaxies. They possess a set of common properties, namely luminosity, spectral energy distribution, and morphology which characterise them as a *true coherent population of galaxies*, and they are currently *the best candidates for the population of primeval galaxies at redshift z > 3*. We have spectroscopically confirmed that among these candidates there are objects at redshifts $z > 3$. Furthermore, we have found empirical evidence for the existence of clusters of galaxies at a redshift as high as $z \sim 3.4$. These structures are not predicted to exist at such an early epoch under many theories of galaxy formation. If confirmed by other detections (we are currently working on new fields), these findings will have profound consequences on our understanding of large-scale structure formation and evolution.

With the current sensitivity of the ground-based telescopes, we have access only to the bright end of the luminosity distribution of these galaxies, namely galaxies with $L > 2$–$3\ L^*$, resulting in very few spectroscopically confirmed detections. Nevertheless, the different pieces of evidence that we have obtained allow us to be very confident in the assertion that we have detected the bright-end of the population of normal galaxies during their early phase of star formation. While we do not yet know whether or not these are the *primeval galaxies*, namely the very first galaxies to form, we are confident that follow-up work with the ESO telescopes and the HST will allow us to build a more meaningful picture for the evolution of galaxies in the early Universe.

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Discovery of a Supernova (SN 1995K) at a Redshift of 0.478

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Three main cosmological parameters govern all models of an expanding Universe. They are the current expansion rate, the Hubble constant H_0, the derivative of this rate, the deceleration parameter q_0, and the vacuum energy density, the cosmological constant Λ_0. Measuring these parameters has been one of the main goals of observational cosmology for the last few decades. As more accurate values of the Hubble constant become available, attention is shifting to the second measurable q_0 which, in a Universe with negligible Λ_0, is directly linked to the mean density of the Universe (Ω_0).

Reliable distances are needed for a plausible determination of both q_0 and H_0. While there are now several independent distance indicators which give reliable relative distances out to about the distance of the Coma Cluster, most of these will not work at distances required to measure q_0 primarily due to their limited intrinsic brightness. Type Ia supernovae (SNe Ia) are amongst the more promising distance indicators out to redshifts of about 0.5. SNe Ia exhibit a remarkable uniformity in their light curves and spectra, which, combined with their extremely high luminosities make them ideal standard candles. Recent, accurate observations of the SN light curves, however, show that the intrinsic scatter of the absolute magnitude of Ia supernovae exceeds 0.4 magnitudes. This is probably due to variations in the explosion energy and masses of the progenitors. Such a scatter would make supernovae only mediocre standard candles. It has been shown, however, that the absolute magnitude of a SN Ia is correlated with its light curve shape. This makes it possible to correct supernova magnitudes as long as a well-observed light curve is available. A sample of SNe Ia with redshifts of less than 0.1 follows the expansion relation in the zc vs. m_{max} diagram extremely well and, after the aforementioned correction is applied, with a very small scatter (< 0.2 mag; Hamuy et al., 1995).

We have started a project to search for supernovae at redshifts between 0.3 $< z <$ 0.5 combining several 4-m-class telescopes around the world. The search is conducted with the CTIO 4-m prime focus camera which provides a field of view of 15 arcmin on a side. Short exposures (5 minutes) reach a limiting magnitude of about 23.5 in a special redshifted B filter (almost equivalent to a regular Kron-Cousin R filter). We can observe around 55 fields in one night. Specially designed search software is employed in real time to find suitable candidate objects by comparing the newly acquired frames with reference images obtained on previous runs. Spectroscopic follow up time has been scheduled at the AAT, the MMT, and the NTT at ESO. These nights have been requested to follow shortly after the search nights making it possible to obtain a spectrum of any supernova discovered near maximum. We expect to find most supernovae slightly before peak light due to special spacing of the search nights.

Reference images of the fields were established last February followed by three search nights in February and March. Unfortunately, the weather was clear only during two half nights in March. A good candidate was established during our last search night at CTIO and was followed up two nights later with the NTT. The possibility to use the various modes of EMMI and the high spatial resolution of SUSI during a single observing night allowed us to confirm the existence of the supernova, now designated SN 1995K (Schmidt et al., 1995), in a distant galaxy

[1]now at ESO.