PROPERTIES OF LY-α AND GAMMA RAY BURST SELECTED STARBURSTS AT HIGH REDSHIFTS

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Abstract Selection of starbursts through either deep narrow band imaging of redshifted Ly-α emitters, or localisation of host galaxies of gamma-ray bursts both give access to starburst galaxies that are significantly fainter than what is currently available from selection techniques based on the continuum (such as Lyman-break selection). We here present results from a survey for Ly-α emitters at $z = 3$, conducted at the European Southern Observatory's Very Large Telescope. Furthermore, we briefly describe the properties of host galaxies of gamma-ray bursts at $z > 2$. The majority of both Ly-α and gamma-ray burst selected starbursts are fainter than the flux limit of the Lyman-break galaxy sample, suggesting that a significant fraction of the integrated star formation at $z \approx 3$ is located in galaxies at the faint end of the luminosity function.

Keywords: galaxies:high redshift

1. Introduction

As illustrated in the title of this conference, *From 30-Doradus to Lyman-break galaxies*, the term *Lyman-break galaxy* (LBG) is almost synonymous with *high redshift starburst galaxy*. However, as has been stressed by many authors, including the lead researchers behind the Lyman-break technique, current samples of LBGs consist of starbursts that are extremely luminous in the UV and do not give a complete census of all starbursts at high redshifts. The current magnitude limit in the ground based surveys for LBGs is R(AB)$= 25.5$ (Steidel et al. 2003). The luminosity function of LBGs has been extended to R(AB)≈ 27 based on data from the Hubble Deep Fields (e.g., Adelberger & Steidel 2000). The faint end of this LBG luminosity function is very steep, with a slope $\alpha = -1.6$, implying that more than 70% of the light is emitted by galaxies fainter than R(AB)= 25.5. Furthermore, as discussed at this conference, the most vigorous starbursts at high redshifts, e.g. as observed with SCUBA or with Spitzer, are often obscured in the rest-frame UV (e.g., Chapman et al. 2004) and often hence do not fulfill the selection criteria for LBGs.

How is it then possible to locate and examine starbursts at high redshifts that are missed by the Lyman-break technique? One other method, not mentioned at this conference, is absorption selection of galaxies. The few galaxy counterparts that so far have been identified for Damped Ly-α Absorbers (DLAs), found in QSO spectra, appear to be starburst galaxies with significantly smaller luminosities than LBGs (e.g., Møller et al. 2004; Weatherley et al. 2005). However, the total cross section of DLAs at $z \approx 3$ is much larger than what can be accounted for by LBGs. This implies that most of the neutral gas available for star formation at these redshifts is located in galaxies fainter than the LBG flux limit (Fynbo et al. 1999). Other papers in these proceedings discuss the dust emission selected galaxies. Here we will discuss *i)* selection of Ly-α emitting starbursts through deep narrow band imaging, and *ii)* localisation of gamma-ray burst (GRB) host galaxies.

2. Ly-α selection of high redshift starbursts

The idea to use Ly-α to search for primordial galaxies dates back to the 1960s (Partridge & Peebles 1967). The first detection of redshifted Ly-α emission from galaxies not powered by active galactic nuclei (AGN) were serendipitous discoveries resulting from searches for galaxy counterparts of QSO absorbers such as DLAs and Lyman-limit systems (Lowenthal et al. 1991; Møller & Warren 1993; Francis et al. 1996; Fynbo et al. 2001; Francis et al. 2004). Other Ly-α emitters were serendipitously discovered during searches for intracluster planetary nebulae (Kudritzki et al. 2000). This curiosity reflects the fact that for many years it was considered impossible to locate galaxies by their Ly-α emission as the probability for Ly-α photons to be absorbed by dust, due to resonant scattering, is much larger than for continuum photons. The first dedicated search for Ly-α emitters with 8–10 m class telescopes was conducted at the Keck telescope (Hu et al. 1998).

The "Building the Bridge" Survey

In 2000, some of the authors started the program "Building the Bridge between Damped Ly-α Absorbers and Lyman-Break Galaxies: Ly-α Selection of Galaxies" at the European Southern Observatory's Very Large Telescope (VLT). This project is an attempt to use Ly-α selection to bridge the gap between absorption- and emission-line selected galaxies by characterisation of $z \approx 3$ galaxies, possibly corresponding to the abundant population of faint

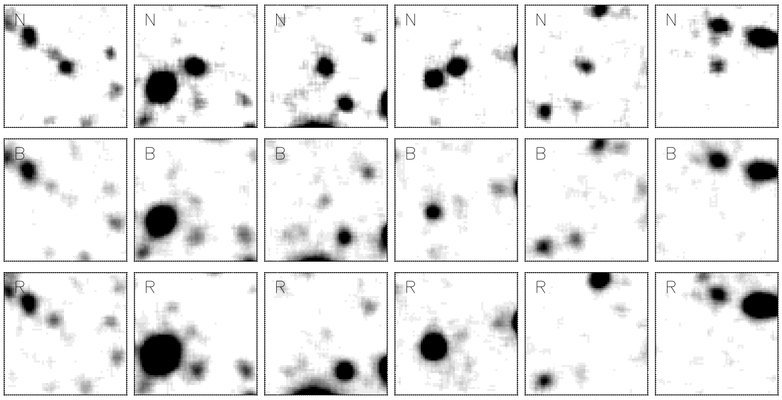

Figure 1. Six examples of spectroscopically confirmed $z = 2.85$ Ly-α emitters from the "Building the Bridge Survey" (see Fynbo et al. 2003a for more information including spectra of the sources). The size of each image is 12×12 arcsec^2. The upper row shows narrow band images of the galaxies, middle row the B-band images and the bottom row the R-band images. About $\sim 20\%$ of the LEGOs remain undetected in the broad bands despite 5σ detection limits of $\mathrm{B(AB)} = 27.0$ and $\mathrm{R(AB)} = 26.4$.

($\mathrm{R} > 25.5$) galaxies associated to DLAs (Fynbo et al. 1999; Haehnelt et al. 2000). The survey consists of very deep narrow band observations of three fields at $z = 2.85$, $z = 3.15$, and $z = 3.20$. In each of these fields, we have detected and spectroscopically confirmed ~ 20 Ly-α emitters, or LEGOs (acronym for *Ly-α Emitting Galaxy-building Object*). In Fig. 1 we show six examples of LEGOs from the $z = 2.85$ field. Of the total sample, 85% are fainter than the flux limit for LBGs. Furthermore, as only $\approx$25% of the LBGs have Ly-α emission lines with equivalent widths large enough to fulfill our selection criterion for LEGOs (Shapley et al. 2003), it is clear that LBGs and LEGOs are almost disjunct classes of high redshift starbursts.

LEGOs in the GOODS Field South

Given that most LEGOs are extremely faint, it is very difficult to establish any property beyond the Ly-α flux for individual galaxies, even with 8–10 m class telescopes. For this reason, we decided to observe a field with existing, very deep broad band observations covering most of the electromagnetic spectrum, namely the GOODS Field South (Giavalisco et al. 2004). In 2002 we obtained observations of a section of the GOODS Field South. Due to bad weather, we did not reach the same flux limit as for the "Building the Bridge" fields, but still we detected nearly 20 candidate $z = 3.20$ LEGOs in the field.

The analysis of the broad band properties of these candidates constitute the thesis work of two of the authors (B. Krog and K. Nilsson). Here we report a

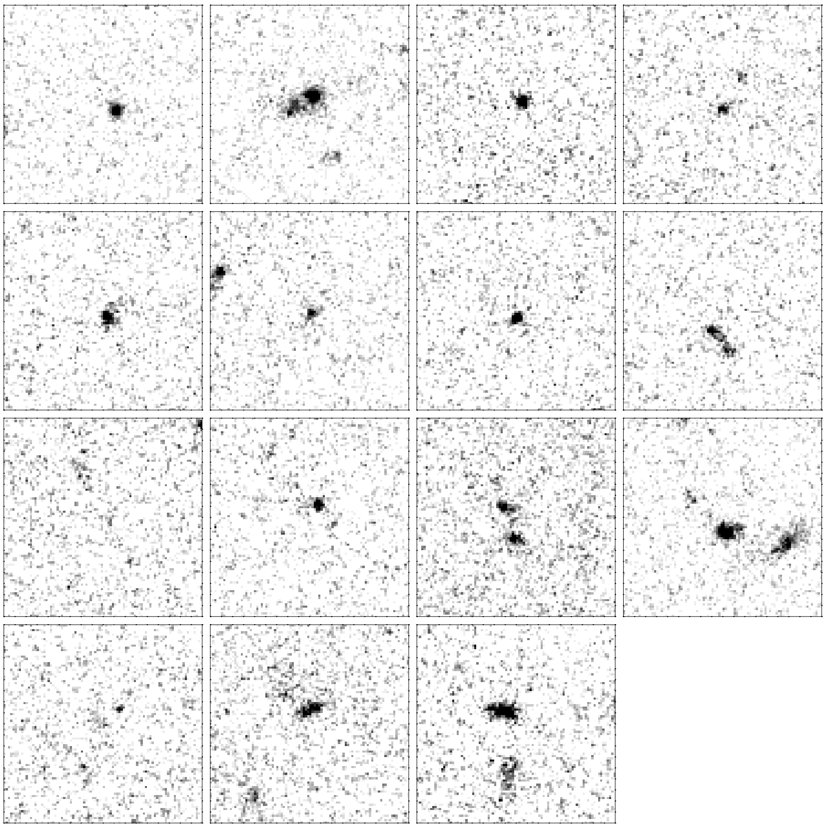

Figure 2. HST/ACS V-band images of size $3{\times}3$ arcsec^2 around the positions of 15 of the candidate $z = 3.20$ LEGOs in part of the GOODS Field South . The V(AB) magnitudes range from $\sim$26 to $>$29.

few preliminary results. So far the objects have been studied in X-rays (Chandra X-ray Observatory, 1 Ms exposure), near-IR (VLT/ISAAC), and the optical broad bands (HST/ACS). The HST images (Fig. 2) confirm that the LEGOs have extremely faint continua in the range V(AB)= 26–29. Furthermore, *i)* these galaxies are bluer than most LBGs, with spectra that rise toward the blue ($F_\nu \propto \nu^\beta, \beta < 0$) implying younger ages and/or lower dust content than what is typical for LBGs, and *ii)* they have extremely compact morphologies and sometimes consist of several knots similar to the LBGs (e.g., Lowenthal et al. 1997). Only upper limits were found in the X-ray and near-IR images so we can exclude that the galaxies harbour AGN and significant older populations of stars. We are currently working on deriving stronger constraints from stacking of the individual sources.

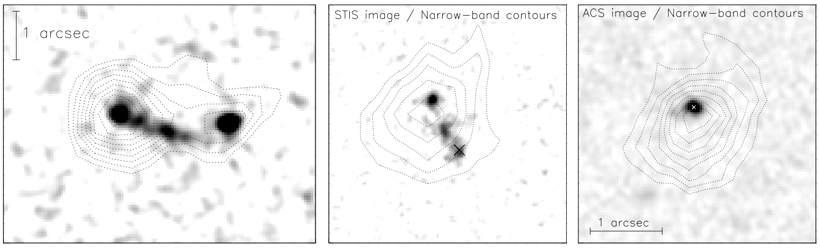

Figure 3. HST images of the host galaxies of GRBs 000926 ($z = 2.04$, R(AB)= 24.0), 011211 ($z = 2.14$, R(AB)= 25.0), and 021004 ($z = 2.33$, R(AB)= 24.4). The contours show the morphology of Ly-α emission, as measured by ground-based narrow band imaging (Fynbo et al. 2002; Fynbo et al. 2003b; Jakobsson et al. in prep). GRB 000926 occurred near the centre of the right-most knot. The locations of GRB 011211 and GRB 021004 are marked with crosses. The field sizes for the GRB 011211 and GRB 021004 images are the same.

3. GRB selection of starbursts

GRBs are short, extremely energetic bursts of γ-rays associated with energetic core-collapse supernovae (Hjorth et al. 2003). If the GRB rate is directly proportional to the (massive) star formation rate, then the properties of GRB hosts should reflect the diversity of all star-forming galaxies in terms of luminosity, environment, internal extinction and star formation rate. GRB hosts therefore constitute a central clue for our understanding of galaxy formation and evolution (e.g., Ramirez-Ruiz et al. 2002; Tanvir et al. 2004; see also the papers by Tanvir et al. and Trentham et al. in these proceedings).

The prompt burst of γ-rays is followed by a so-called afterglow, emitting over a very wide spectral range from radio through the optical/near-IR to X-rays (see van Paradijs et al. 2000 for a review). The afterglow can be extremely bright, allowing a precise localisation on the sky. More importantly, spectroscopy of the afterglow can give information about the redshift and the physical conditions within the host, and in intervening absorption systems along the line of sight (see, e.g., Vreeswijk et al. 2004 and Jakobsson et al. 2004a for examples). When the GRB has faded, the host galaxy itself can be observed. The measured redshifts for GRBs cover a very broad range from $z = 0.0085$ to $z = 4.50$ with a median around $z = 1.1$ (e.g., Jakobsson et al. 2004a).

How do GRB hosts compare to LBGs and LEGOs? So far, the redshift has been measured for 10 $z > 2$ GRBs. HST-images of the three brightest of these are shown in Fig. 3. For the remaining seven, the host is either undetected to faint magnitude limits or have a magnitude fainter than R(AB)= 26, so the majority of these GRB hosts are fainter than LBGs. Remarkably, all current evidence is consistent with the conjecture that GRB hosts are Ly-α emitters (Fynbo et al. 2003b). As shown in Fig. 3, the three brightest high redshift

GRB hosts are Ly-α emitters, and for the remaining seven, Ly-α emission has either been detected (2 hosts) or not yet searched for to sufficient depth to allow detection of even a large equivalent width emission line (5 hosts). Taken at face value, this suggest that faint, LEGO-like galaxies in total account for the majority of the star formation at these redshifts. However, there could be other explanations for why GRBs have, so far, mainly been localised in such galaxies (Fynbo et al. 2003b). In particular, some of the so-called dark bursts could be located in more massive and dust-obscured galaxies (e.g., Tanvir et al 2004; Jakobsson et al. 2004b and references therein). The recently launched Swift satellite (Gehrels et al. 2004) offers a unique chance to resolve this issue.

4. Summary

In conclusion, surveys for LEGOs and for GRB host galaxies reveal that a major fraction of the starburst activity at $z > 2$ may be located in galaxies fainter than the flux limit of the LBG survey. We have here shown that Ly-α emission and GRB selection are two viable methods to probe this population of faint starbursts at high redshifts.

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