NEAR-ULTRAVIOLET SOURCES IN THE GREAT OBSERVATORIES ORIGINS DEEP SURVEY FIELDS

D. F. de Mello,1,2,3 T. Dahlen,4 Jonathan P. Gardner,1 and N. A. Grogan3

Received 2006 March 17; accepted 2006 July 17

Abstract

We present an ultraviolet-selected sample of 268 objects in the two fields of the Great Observatories Origins Deep Survey (GOODS). We used the parallel observations taken with the Wide Field Planetary Camera 2 in the U band (F300W), which covered 88% of the GOODS fields, to identify sources and selected only objects with GOODS Advanced Camera for Surveys counterparts. Spectrophotometric redshifts for 95 of these sources are available, and we have used the multiwavelength GOODS data to estimate photometric redshifts for the others. Most of the objects have redshifts 0.2 < z < 0.8. We used the spectral types obtained by photometric redshift fitting to identify starburst galaxies. We have also visually checked all objects and looked for tidal effects and nearby companions. We find that (1) 45% of the UV-selected galaxies are starbursts, (2) nearly 75% of the starbursts have tidal tails or show some peculiarity typical of interactions or mergers, and (3) ~50% have companions within an area of 5″ × 5″. The UV-selected sample has an average rest-frame $M_B = -19.9 \pm 0.1$. The bluest objects in the sample ($U - B < 0.2$ and $B - V < 0.1$) are at $1.1 < z < 1.9$ and have peculiar morphologies that resemble either tadpoles, chains, or double-clump galaxies. Starbursts with tadpole or clump morphologies at $z = 0.8$–1.3 have sizes comparable to Lyman break galaxies and compact UV-luminous galaxies.

Key words: galaxies: evolution — galaxies: formation — galaxies: starburst

Online material: machine-readable table

1. INTRODUCTION

One of the open questions in modern astronomy is when galaxies acquired their morphology and how star formation and morphology correlate. Are star-forming galaxies at higher $z$, such as Lyman break galaxies (LBGs), related to local starburst galaxies, or are there evolutionary effects that prevent correlating the two populations? Heckman et al. (2005) attempted to identify the local equivalents of LBGs using images from the UV satellite Galaxy Evolution Explorer (GALEX) and spectroscopy from the Sloan Digital Sky Survey. They found a class of nearby ($z < 0.3$) UV-luminous compact starburst galaxies (compact UVLGs) that resembles the LBGs at $z \sim 2$–3. No local galaxy population meets the UV-luminous criteria, which makes these objects a class of scaled-up unobscured starbursts just like LBGs. If these objects are common out to $z < 1$–2 they could contribute significantly to the rise of the star formation rate density in the universe. Recently, Burgarella et al. (2006), using GALEX, the Spitzer Space Telescope, the Hubble Space Telescope (HST), and ground-based telescopes, selected a sample of ~300 far-UV sources in the Chandra Deep Field–South (CDF-S) that resemble LBGs at $z \sim 1$. Their sample contains not only UVLGs but also lower luminosity LBGs. However, they were able to obtain morphology for only 36 LBGs, since only one-fourth of their GALEX field was observed with HST. In this article we provide a sample of 268 near-UV sources detected in the two Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) fields, for which there is extensive multiwavelength coverage. Our goal is to select enough star-forming galaxies at intermediate $z$ to characterize their role in galaxy evolution.

2. THE DATA

During the GOODS campaign with HST we implemented a Wide Field Planetary Camera 2 (WFPC2) pure parallel program aimed at covering the lack of U-band observations with the Advanced Camera for Surveys (ACS) and maximizing the synergy between the parallels and the prime instrument. We took near-UV images with the F300W filter ($U$ band with $\lambda_{\text{max}} = 2920$ Å) in parallel from both fields from 2002 December until 2003 March. GOODS HST images, also aimed at searching for high-z supernovae (Strolger et al. 2004), were taken in five repeat visits separated by approximately 45 days. The two GOODS fields were observed with the F435W ($B$), F606W ($V$), F775W ($i$), and F850LP ($z$) filters. The exposure times were 3, 2.5, 2.5, and 5 orbits per filter, respectively. The observations included the Hubble Deep Field–North (HDF-N) and the CDF-S, and each field had 15 ACS fields of view, which makes GOODS 320 arcmin$^2$ in extent.

Due to the multiphase nature of the GOODS observations, the WFPC2 coverage was not uniform and covered ~88% of the two fields. Figures 1 and 2 show the overlap between the WFPC2 observations and the ACS images.

We retrieved a total of 741 WFPC2 images from the HST archive, which were reduced using the HST pipeline. We separated all images that were centered within <0.1 of each other and dithered them using the package PyDrizzle, which provides an automated method for dither-combining and distortion-correcting images. The quality of the drizzled image was checked by analyzing the point-spread function of a few stars present in some of the images.

A total of 30 WFPC2 drizzled images of the GOODS-South (GOODS-S) field and 25 of the GOODS-North (GOODS-N) field were produced. The exposure times of each drizzled image varied from 800 to 11,100 s, with a typical exposure time being
~2000 s. The deep mosaic with 11,100 s falls mostly outside the GOODS-N field.

Throughout this paper, we use a cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $h = 0.7$. Magnitudes are given in the AB system.

3. SAMPLE

We detected sources on the drizzled images using SExtractor, version 2.2.2 (hereafter SE; Bertin &Arnouts 1996). Our detection criterion was that a source must exceed a 1.5 $\sigma$ sky threshold in 5 contiguous pixels; we also used a detection filter with a Gaussian FWHM of 4 pixels. We used SE’s \texttt{mag\_auto} function, which is calculated using a flexible elliptical aperture around every detected object, and obtained the magnitude error, $\Delta m$, using SE’s rms calculated with \texttt{background\_rms}.

The next step was to match the WFPC2 $U$-band coordinates with the GOODS ACS detections. The GOODS catalog is $z$-band based with matched aperture photometry in the ACS $B$, $V$, and $i$ bands. We adopted a maximum offset radius of 1.5” between the WFPC2 and ACS coordinates. In this paper we analyze only the $U$-band-selected objects that have ACS counterparts. Due to
the shallowness and the heterogeneous nature of the parallel data we decided to focus on the bright end by imposing a conservative magnitude limit to the sample. The magnitude limit $\text{mag}_{\text{auto}} < 24.5$ and error $\Delta m_{\text{AB}}(\text{F300W}) < 0.10$ were set to guarantee a clear identification even in the shallowest F300W images. The final catalog has 130 objects in the GOODS-S and 138 in the GOODS-N. We have excluded duplicated objects that were in the borders of the drizzled images and were present in more than one field by choosing the one with either higher exposure time or lower magnitude error. Figure 3 shows the distribution of magnitudes as a function of exposure times. Despite the imposed magnitude limit at 24.5 we included two faint objects with magnitudes lower than the limit ($\text{mag}_{\text{auto}} = 25.63$ and 25.96), since they are in the deepest F300W image and $\Delta m_{\text{AB}}(\text{F300W}) < 0.10$.

We have identified 42 objects as stars based on their surface brightness versus magnitude relation. A total of 32 are in the southern field, and 10 in the northern field. Some of these objects are active galactic nuclei (AGNs) but are not further analyzed in this paper.

For comparison, the deepest near-UV image, obtained with 323.1 ks of HST time as part of the parallel observations of the Hubble Ultra Deep Field (UDF) campaign (de Mello et al. 2006),
Photic redshifts were calculated using the template-fitting method described in detail by Dahlen et al. (2005). The template spectral energy distributions (SEDs) used cover spectral types (STs) E, Sbc, Scd, and Im (Coleman et al. [1980], with plate spectral energy distributions (SEDs) used to cover spectral type fitting when deriving the photometric redshifts is shown in Figure 6 is within the redshift accuracy of GOODS (Dahlen et al. 2005). We have checked the four objects with the most discrepant redshifts and concluded that the main reason for the discrepancy is either the presence of bright companions that make the photometry of the objects less accurate, or confusion on the slit when the spectra were taken.

The distribution of the STs that were obtained from the template fitting when deriving the photometric redshifts is shown in Figure 7. As expected in the case of UV-selected samples, the majority (~48%) of the objects are starbursts (ST > 4.5). In fact, the fraction of starbursts could be even higher, since a starburst galaxy with a high internal extinction has a redder SED and may be shifted to an earlier spectral type with ST < 4.5. A few galaxies with early-type SEDs (~5% have ST < 1.5) are also present in the UV-selected sample. These early-type objects with star-forming cores could be the result of mergers or star formation triggered by the rapid mass infall into a central black hole, as suggested in Menanteau et al. (2001). For comparison, Burgarella et al. (2006) found that LBGs at z ~ 1 are either disks (75%) or mergers (22%), and only one object (3%) is a spheroid.

5. STARBURSTS

In order to assess the nature of the galaxies that are forming stars at intermediate z we have visually inspected all 93 objects with starburst SEDs, classified them according to their optical morphology, and searched their environment (5" x 5") for other objects. We did the analysis in the GOODS bands (B, V, i, and z), since far-UV morphologies can give an erroneous view of the

| R.A. | Decl. | Exp (s) | U | U$_{err}$ | B | B$_{err}$ | V | V$_{err}$ | i | i$_{err}$ | z | z$_{err}$ | z$_{phot}$ | ST | z$_{spec}$ |
|-----|------|--------|---|---------|---|---------|---|---------|---|---------|---|---------|-----------|----|----------|
| 53.1025057 | −27.7411446 | 800 | 23.38 | 0.05 | 23.30 | 0.04 | 22.61 | 0.02 | 22.03 | 0.02 | 21.86 | 0.02 | 0.51 | 3.7 | 0.54 |
| 53.1056270 | −27.7507864 | 2400 | 23.48 | 0.05 | 23.09 | 0.03 | 23.12 | 0.02 | 22.69 | 0.02 | 22.51 | 0.02 | 1.12 | 6.0 | 0.97 |
| 53.1258995 | −27.7512749 | 2260 | 23.17 | 0.02 | 22.55 | 0.02 | 22.03 | 0.01 | 21.62 | 0.01 | 21.40 | 0.01 | 0.43 | 5.3 | 0.29 |
| 53.1237751 | −27.7520043 | 2260 | 23.92 | 0.06 | 23.60 | 0.03 | 23.10 | 0.02 | 22.39 | 0.02 | 22.20 | 0.02 | 0.70 | 3.7 | 0.74 |
| 53.1952443 | −27.7537776 | 1500 | 22.72 | 0.02 | 23.96 | 0.04 | 23.26 | 0.02 | 22.26 | 0.02 | 21.82 | 0.02 | 0.89 | 2.7 | 0.84 |

Notes.—Units of right ascension and declination are degrees. Table 1 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

5 See http://www.eso.org/science/goods/spectroscopy/CDFS-Mastercat.
Fig. 4.—Photometric redshift distribution for the northern (solid line) and southern (dotted line) fields.

Fig. 5.—Spectroscopic redshift distribution for the northern (solid line) and southern (dotted line) fields.

Fig. 6.—Photometric and spectroscopic redshifts for the northern (circles) and southern (triangles) fields.

Fig. 7.—ST distribution for the UV-selected galaxies in the two GOODS fields. E (1), Sbc (2), Scd (3), and Im (4) are from Coleman et al. (1980). Spectral type 5 corresponds to either of the two starburst templates from Kinney et al. (1996).
galaxy’s shape (e.g., Hibbard & Vacca 1997). We found that (1) nearly 75% of the starbursts have tidal tails or show some peculiarity typical of interaction/mergers, and (2) ~50% have another galaxy within the searched area.

We also found that ~36% of the starbursts are characterized by the presence of a large clump and extended tail, known as a tadpole. Very little is known about these objects and their fate during evolution. The main question is whether such galaxies are rotating edge-on systems or objects with peculiar morphology from merging or accretion (Elmegreen et al. 2004, 2005). We discuss these objects in more detail in §6.

Although our photometric redshifts are well calibrated with spectroscopic redshifts within the GOODS collaboration (>1000 redshifts for both GOODS fields), the featureless spectra of starbursts, compared to earlier type galaxies with a pronounced 4000 Å break, make their photometric redshift estimates uncertain with an increased risk of ”catastrophic redshifts” with large errors. In order to prevent any bias due to the photometric redshift estimates, we were conservative and repeated our analysis for the 95 objects with known spectroscopic redshifts and found that (1) 35% are starbursts, and (2) 66% of the starbursts show some obvious tidal effect and/or presence of another galaxy within the searched area. Only 33% of the other spectral types show tidal tails and/or the presence of other galaxies within the same area.

Figure 8 shows a gallery of starbursts from the CDF-S with spectroscopic redshifts at \( z = 0.37 \pm 0.34 \). Galaxies of all types are represented in the starburst gallery. For example, we can see an early-type galaxy (object 3) and a merging system (object 4), disk galaxies with strong knots of star formation (objects 1, 5, and 7), and compact objects or clumps with tidal tails (objects 6 and 9). Strong interacting systems such as objects 1 and 2 are also common in the UV-selected sample of starbursts.

6. DISCUSSION

Using information from the photometric redshifts or spectroscopic redshifts when available, rest-frame absolute magnitudes and colors are calculated using the prescription in Dahlen et al.
are marked with circles and the southern field with triangles. Only galaxies with
(i.e., starburst galaxies) are marked with large symbols. The northern field objects
are brighter than only to the bright end of the luminosity distribution, none of the
fact that the shallow
(2005). However, we only analyzed the ones with $z_{\text{phot}} < 2$, since photometric redshift uncertainties are larger for higher redshifts. Figure 9 shows the rest-frame $U - B$ versus $B - V$ color for both fields. The bluest objects ($U - B < 0.2$ and $B - V < 0.1$) have spectral types of starbursts, except for one object (object 2 in Fig. 9) with spectral type Im, which is also star forming and UV bright.

The bluest objects are also marked in the color-magnitude plot shown in Figure 10, where we have also identified objects from Bershady et al. (2000), which includes typical Hubble types, dwarf elliptical galaxies, and luminous blue compact galaxies at intermediate redshifts. A large number of the UV-selected sample fit the latter category, which Bershady et al. described as blue nucleated galaxies, compact narrow emission-line galaxies, and small, blue galaxies at intermediate redshifts. A similar color-magnitude plot was presented in de Mello et al. (2006, their Fig. 13) in the analysis of the deepest $U$-band image ever taken with HST. The main difference between their color-magnitude distribution and Figure 10 is that the shallow $U$-band survey, presented here, detected a larger number of brighter and bluer objects than the deep survey. This is expected, since the wide survey covers a much larger area (the deep survey is only slightly larger than one WFPC2 field) and is sensitive only to bright galaxies. The average rest-frame $M_B$ value for the shallow $U$ band ($M_B = -19.91 \pm 0.10$) is 1 mag brighter than the average value of the deep $U$ band ($M_B = -18.43 \pm 0.13$). Despite the fact that the shallow $U$ band covers a larger area and is sensitive only to the bright end of the luminosity distribution, none of the UV-selected galaxies in the GOODS fields are brighter than $M_B = -23$.

The bluest objects are at $z = 1.1 - 1.9$ and, as shown by the contours in Figure 11, have peculiar morphologies that resemble either tadpoles, chains, or double-clump galaxies. These galaxies are characterized by the presence of a large clump and extended tail, or two or more large clumps in a linear arrangement. Like the objects in the UDF and the Tadpole ACS field analyzed

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig9}
\caption{Rest-frame $U - B$ vs. $B - V$ color. Galaxies with spectral types >4.5 (i.e., starburst galaxies) are marked with large symbols. The northern field objects are marked with circles and the southern field with triangles. Only galaxies with $z_{\text{phot}} < 2$ were included. The bluest objects are identified by numbers 1–9.}
\end{figure}

by Elmegreen et al. (2004, 2005), their unusual morphology is not merely a band-shifting effect, since the large clumps have no counterparts in the local universe as seen in the UV nearby-galaxy survey (Windhorst et al. 2002). The main question is whether these clumps are accreted clumps that are building up galaxies through hierarchical mergers (Straughn et al. 2006; Elmegreen et al. 2004; Elmegreen & Elmegreen 2005) or the result of gravitational instabilities of gas accreting in a turbulent medium in a disk (e.g., Noguchi 1996; Immeli et al. 2004). These questions could be answered in the future with near-IR spectroscopy.

There are 12 galaxies in our sample in the redshift range $z = 0.8 - 1.3$, and they are either interacting systems, such as object 4 in the starburst gallery, or have the tadpole/clump morphology discussed above. Figures 12 and 13 show six of these objects in the $B$ and $z$ bands. At $z \sim 1$ the $B$ band shows the rest-frame near-UV morphology, while the $z$ band shows the morphology in the rest-frame $B$ band. The contours show that the morphologies are similar in both bands.

The average total magnitudes and half-light radii of these objects are $M_B = -20.21 \pm 1.11$ and $1.63 \pm 0.37$ kpc (measured in the $B$ band), respectively. These starbursts at $z = 0.8 - 1.3$ have sizes comparable to LBGs and compact UVLGs.

7. SUMMARY

We present a sample of 268 objects, including 42 stars or AGNs, in the GOODS-North and GOODS-South fields that was selected from “shallow” images taken with the $U$-band filter (F300W) during the WFPC2 parallel observations of the GOODS ACS campaign. The analysis of the ACS images ($B$, $V$, $i$, and $z$) of these UV-selected objects reveals that

1. Most of the objects have redshift $0.2 < z < 0.8$. 

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig10}
\caption{Rest-frame magnitude $B$ vs. $B - V$ color. Galaxies with spectral types >4.5 (i.e., starburst galaxies) are marked with large symbols. The northern field objects are marked with circles and the southern field with triangles. The three squares are values typical of E, Sa-Sb, and Sc-Irr (clockwise); the cross at the top left corresponds to the dE and dSph types; and the boxed region corresponds to the strongly star-forming galaxies (Bershady et al. 2000), including blue nucleated galaxies, compact narrow emission-line galaxies, and small, blue galaxies at intermediate redshifts. Only galaxies with $z_{\text{phot}} < 2$ were included. Numbers 1–9 are the same objects as in Fig. 9.}
\end{figure}
Fig. 11.—Contours on top of z-band images of the bluest objects in the $U - B$ vs. $B - V$ plot shown in Fig. 9. All objects have STs of starburst galaxies, except for object 2, which has the ST of an Im galaxy. Contour limits are minimum = 0.002 and maximum = 0.01, with five levels, except for objects 3 and 5, which have maximum values 0.1 and 0.05, respectively, and nine levels. The size of each image is 76 pixels $\times$ 53 pixels.
Fig. 12.—Contours on top of B-band images of the tadpole starburst galaxies at z ~ 1. Coordinates are given for each object.
2. The majority (45%) of the galaxies have spectral types of starburst galaxies; however, galaxies of all spectral types are found, including early types (5%).

3. Of the starburst galaxies, 75% have tidal tails or show some peculiarity typical of interaction/mergers, and 50% have another galaxy within $5000 \pm 500$.

4. The bluest galaxies ($U - B < 0.2$ and $B - V < 0.1$) are at $1.1 < z < 1.9$ and have peculiar morphologies that resemble either tadpoles, chains, or double-clump galaxies.

5. Starburst galaxies at $z \sim 1$ with tadpole/clump morphology have half-light radii of $1.6 \pm 0.4$ kpc.

We are grateful to the GOODS team. Support for this work was provided by NASA through grants GO09583.01-96A and GO09481.01-A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

REFERENCES

Bershady, M. A., Jangren, A., & Conselice, C. J. 2000, AJ, 119, 2645
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bolzonella, M., Miralles, J.-M., & Pelló, R. 2000, A&A, 363, 476
Burgarella, D., et al. 2006, A&A, 450, 69
Coleman, G. D., Wu, C.-C., & Wedman, D. W. 1980, ApJS, 43, 393
Dahlen, T., Mobasher, B., Somerville, R. S., Moustakas, L. A., Dickinson, M., Ferguson, H. C., & Giavalisco, M. 2005, ApJ, 631, 126
de Mello, D. F., Wadadekar, Y., Casertano, S., & Gardner, J. P. 2006, AJ, 131, 216
Elmegreen, B. G., & Elmegreen, D. M. 2005, ApJ, 627, 632
Elmegreen, D., Elmegreen, B., Rubin, D., & Schaffer, M. 2005, ApJ, 631, 85
Elmegreen, D. M., Elmegreen, B. G., & Sheets, C. M. 2004, ApJ, 603, 74
Giavalisco, M., et al. 2004, ApJ, 600, L93
Heckman, T. M., et al. 2005, ApJ, 619, L35
Hibbard, J. E., & Vacca, W. D. 1997, AJ, 114, 1741
Immel, A., Samland, M., Westera, P., & Gerhard, O. 2004, ApJ, 611, 20
Kinney, A., Calzetti, D., Bohlin, R. C., McQuade, K., Storehi-Bergmann, T., & Schmidt, H. R. 1996, ApJ, 467, 38
Menanteau, F., Abraham, R. G., & Ellis, R. S. 2001, MNRAS, 322, 1
Noguchi, M. 1999, ApJ, 514, 77
Somerville, R. S., Lee, K., Ferguson, H. C., Gardner, J. P., Moustakas, L. A., & Giavalisco, M. 2004, ApJ, 600, L171
Straughn, A. N., Cohen, S. H., Ryan, R. E., Hathi, N. P., Windhorst, R. A., & Jansen, R. A. 2006, ApJ, 639, 724
Strolger, L.-G., et al. 2004, ApJ, 613, 200
Windhorst, R., et al. 2002, ApJS, 143, 113
Wirth, G. D., et al. 2004, AJ, 127, 3121