The Subaru Lyα blob survey: A sample of 100 kpc Lyα blobs at z = 3*

Y. Matsuda,† T. Yamada, T. Hayashino, R. Yamauchi, Y. Nakamura, N. Morimoto, M. Ouchi,‡ Y. Ono, K. Kousai, E. Nakamura, M. Horie, T. Fujii, M. Umemura, and M. Mori

1Department of Physics, Science Site, Durham University, South Road, Durham, DH1 3LE
2Astronomical Institute, Graduate School of Science, Tohoku University, Aramaki, Aoba-ku, Sendai 980-8578, Japan
3Research Center for Neutrino Science, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan
4Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101, USA
5Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan
6Department of Astronomy, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
7Center for Computational Sciences, University of Tsukuba, Tsukuba 305-8577, Japan

Accepted ... ; Received ... ; in original form ...

ABSTRACT

We present results of a survey for giant Lyα nebulae (LABs) at z = 3 with Subaru/Suprime-Cam. We obtained Lyα imaging at z = 3.09 ± 0.03 around the SSA22 protocluster and in several blank fields. The total survey area is 2.1 square degrees, corresponding to a comoving volume of 1.6 × 10^6 Mpc^3. Using a uniform detection threshold of 1.4 × 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2} for the Lyα images, we construct a sample of 14 LAB candidates with major-axis diameters larger than 100 kpc, including five previously known blobs and two known quasars. This survey triples the number of known LABs over 100 kpc. The giant LAB sample shows a possible "morphology-density relation": filamentary LABs reside in average density environments as derived from compact Lyα emitters, while circular LABs reside in both average density and overdense environments. Although it is hard to examine the formation mechanisms of LABs only from the Lyα morphologies, more filamentary LABs may relate to cold gas accretion from the surrounding inter-galactic medium (IGM) and more circular LABs may relate to large-scale gas outflows, which are driven by intense starbursts and/or by AGN activities. Our survey highlights the potential usefulness of giant LABs to investigate the interactions between galaxies and the surrounding IGM from the field to overdense environments at high-redshift.

Key words: galaxies: formation – galaxies: evolution – cosmology: observations – cosmology: early universe

1 INTRODUCTION

Lyα blobs (LABs) are spatially extended Lyα nebulae seen in the high-redshift Universe (e.g., Francis et al. 1996; Keel et al. 1996; Steidel et al. 2000; Palunas et al. 2004; Matsuda et al. 2004; Dev et al. 2005; Nilsson et al. 2006; Greve et al. 2007; Smith & Jarvis 2007; Prescott, Dev., & Jannuzi 2009; Yang et al. 2009). LABs are thought to relate to the formation of massive galaxies (Dev et al. 2005; Matsuda et al. 2006) and to be indicative of strong interactions between the inter-galactic medium (IGM) and galaxies with intense star-formation activities and/or AGNs (Furlanetto et al. 2005). To explain the formation mechanisms of LABs, at least three possible ideas have been proposed: cold gas accretion, galactic winds, and photoionization by central galaxies or by AGNs (Haiman, Spaans, & Quataert 2000; Chapman et al. 2001; Taniguchi & Shioya 2003; Chapman et al. 2001). In spite of extensive observational and theoretical efforts in the decade after the first discovery of LABs, the formation mechanisms of LABs are still controversial (Mori & Umemura 2004; Geach et al. 2004; Dijkstra & Loeb 2006; Taniguchi & Shioya 2003; Chapman et al. 2001). Among the LABs, special attention have been given to the largest examples with the spatial extents of ∼ 100 –
200 kpc (hereafter giant LABs) because of their spectacular morphologies and possible association with protoclusters (Steidel et al. 2000; Palunas et al. 2004; Prescott et al. 2008). It is therefore difficult to examine their statistical properties. In order to construct a statistically reliable sample of giant LABs and test their possible association with overdense environments, we undertook a deep, wide-field Ly$\alpha$ imaging at $z = 3.1$.

In this letter, we use AB magnitudes and adopt cosmological parameters, $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. In this cosmology, the Universe at $z = 3.1$ is 2.0 Gyr old and 1.0 arcsec corresponds to a physical length of 7.6 kpc at $z = 3.1$.

## 2 OBSERVATIONS AND DATA REDUCTION

We briefly describe our observations and data reduction, although the details will be reported in a separate paper (Yamada et al. in prep). The summary of the observations and data is listed in Table 1. The imaging observations were carried out between September 2002 and October 2005 using Suprime-Cam (Miyazaki et al. 2002) on the 8.2-m Subaru Telescope (Iye et al. 2004). Suprime-Cam has a pixel scale of 0.2 arcsec and a field of view of 34 × 27 arcmin$^2$. We obtained narrow-band (NB497) images for 12 pointings: Great Observatories Origins Deep Survey-North (GOODS-N), Subaru Deep Field (SDF), three fields in Subaru-XMM Deep Survey (SXDS-C, N, and S) and seven fields around SSA22a (SSA22-Sb1-7). The SSA22-Sb1 field was the first field of our survey and centred at SSA22a, which contains the protocluster region at $z = 3.09$ discovered by Steidel et al. (2000). Initial results of the observations in the SSA22-Sb1 have been already published (Hayashino et al. 2004; Matsuda et al. 2004, 2005). The NB497 filter has a central wavelength of 4977 Å and FWHM of 77 ˚A which corresponds to the redshift range for Ly$\alpha$ at $z = 3.062 - 3.126$ (Hayashino et al. 2004). The width of the redshift slice is 59 comoving Mpc. For the SSA22 fields, we obtained broad-band ($B$ and $V$) images in our observing runs. For GOODS-N, we used archival raw $B$ and $V$-band images (Capak et al. 2004). For the SDF and SXDS fields, we used public, reduced $B$ and $V$-band images (Kashikawa et al. 2004; Furusawa et al. 2008).

We reduced the raw data with sdfred (Yagi et al. 2003; Ouchi et al. 2003) and IRAF. We calibrated the astrometry of the images using the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003). For photometric calibration, we used the photometric and spectrophotometric standard stars, SA113, SA115, FEIGE34, Hz44, P177D, GD248, SA95-42, LDS749B, BD+332642, and G24-9 (Oke 1998; Landolt 1992). We corrected the magnitudes using the Galactic extinction map of Schlegel, Finkbeiner, & Davis (1998). We aligned the combined images and smooth with Gaussian kernels to match their seeing to a FWHM of 1 or 1.1 arcsec depending on the original seeing. We made $BV$ images [$B = (2B + V)/3$] for the continuum at the same effective wavelength as NB497 and made $NB_c$ (con-
Table 2. Properties of the 14 giant LAB candidates

| ID             | RA (J2000) | Dec (J2000) | a\(^a\) (kpc) | Area (arcsec\(^2\)) | \(L_{\text{Ly}\alpha}\) (10\(^{43}\) erg s\(^{-1}\)) | \(F^{b}\) | \(\delta_{\text{LAB}}\) | \(z_{\text{spec}}\) | Note |
|----------------|------------|-------------|---------------|---------------------|----------------------|----------|-----------------|-------------|------|
| SSA22-Sb1-LAB1 | 22:17:25.95| +00:12:37.7 | 175           | 181 ± 14           | 8.1 ± 0.6            | 0.56     | 2.7             | 3.099\(^c\) | 8\(\mu m\)/submm\(^a\) |
| SSA22-Sb6-LAB1 | 22:13:48.30| +00:31:32.8 | 166           | 116 ± 9            | 5.8 ± 0.4            | 0.69     | 0.6             | 3.094\(^d\) | —    |
| SSA22-Sb3-LAB1 | 22:17:38.99| +00:13:27.8 | 157           | 137 ± 8            | 6.8 ± 0.3            | 0.59     | 3.7             | 3.091\(^c\) | QSO\(^e\)/Radio\(^f\) |
| SSA22-Sb5-LAB1 | 22:15:33.56| +00:25:16.9 | 147           | 59 ± 7             | 3.8 ± 0.4            | 0.80     | -0.5            | —           | —    |
| SSA22-Sb3-LAB1 | 22:17:59.45| +00:30:55.7 | 126           | 102 ± 8            | 20.4 ± 0.3           | 0.52     | 1.2             | 3.099\(^c\) | —    |
| GOODS-N-LAB1   | 12:35:57.54| +00:10:58.4 | 121           | 47 ± 5             | 5.4 ± 0.5            | 0.77     | 0.9             | 3.075\(^f\) | QSO\(^e\)/X-ray\(^m\) |
| SSA22-Sb2-LAB1 | 22:16:58.37| +00:34:32.0 | 121           | 60 ± 15            | 2.0 ± 0.6            | 0.70     | 1.2             | —           | —    |
| SSA22-Sb2-LAB2 | 22:16:56.40| +00:27:53.3 | 115           | 48 ± 11            | 1.4 ± 0.2            | 0.73     | -0.1            | —           | —    |
| SSA22-Sb1-LAB5 | 22:17:11.66| +00:16:44.4 | 110           | 43 ± 11            | 1.3 ± 0.3            | 0.74     | 1.0             | —           | 8\(\mu m\)/submm\(^a\) |
| SSA22-Sb5-LAB5 | 22:15:30.27| +00:27:43.6 | 107           | 53 ± 7             | 2.1 ± 0.3            | 0.66     | -0.1            | —           | —    |
| SSA22-Sb6-LAB4 | 22:14:09.58| +00:40:54.6 | 107           | 32 ± 4             | 2.0 ± 0.2            | 0.79     | -0.1            | 3.116\(^d\) | —    |
| SSA22-Sb1-LAB3 | 22:17:59.14| +00:15:28.7 | 103           | 75 ± 9             | 5.2 ± 0.2            | 0.48     | 1.7             | 3.096\(^g\) | X-ray\(^f\) |
| SXDS-N-LAB1    | 02:18:21.31| -04:42:33.1 | 101           | 68 ± 5             | 3.3 ± 0.2            | 0.51     | -0.4            | —           | —    |
| SSA22-Sb1-LAB16| 22:17:29.01| +00:07:50.2 | 101           | 28 ± 8             | 0.8 ± 0.2            | 0.80     | -0.2            | 3.104\(^h\) | X-ray\(^f\)/8\(\mu m\)/submm\(^a\) |

\(^a\) Major-axis diameter.  \(^b\) Filamentarity (\(F = 0\) for a circle, \(F = 1\) for a filament, see text for more detail).  \(^c\) Steidel et al. (2003).  \(^d\) this work.  \(^e\) Shen et al. (2007).  \(^f\) Barger et al. (2002).  \(^g\) Matsuda et al. (2003).  \(^h\) Matsuda et al. (2004).  \(^i\) Webb et al. (2009).  \(^j\) Chapman et al. (2001).  \(^k\) Basu-Zych & Scharf (2004).  \(^l\) Condon et al. (1998).  \(^m\) Alexander et al. (2003).  \(^n\) Geach et al. (2003).  \(^o\) Geach et al. (2009).

Figure 2. Pseudo-colour images (\(B\) for blue, \(NB497\) for green, \(V\) for red) of the 14 giant LABs. The size of the images is 40 × 40 arcsec\(^2\) (≈ 300 × 300 kpc\(^2\)). The yellow contours indicate isophotal apertures with a threshold of 1.4 × 10\(^{-18}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\). The white horizontal bar in the lower right image represents the angular scale of 100 kpc (physical scale) at \(z = 3.1\).

The magnitudes and colours are measured with isophotal apertures defined in the \(N_b\) images.

In Fig. 1, we plot the \(BV - NB497\) colours and \(N_b\) magnitudes of the \(N_b\)-detected sources. The solid line represents the colour criterion used for narrow-band excess objects, \(BV - NB497 = 0.7\), which corresponds to an observed equivalent width of \(EW_{\text{obs}} = 80\ \AA\). From these narrow-band excess objects, we make a diameter-limited catalog of 14 LABs down to a major-axis diameter of the isophotal aperture of \(a \geq 13\ \text{arcsec}\) (or \(\geq 100\ \text{kpc}\) at \(z = 3.1\)).

For the LAB selection, we use the major-axis diameters rather than isophotal area, in order to cover LABs with asymmetric structures. For example, cold stream models predicted that LABs have asymmetric, long and thin filamentary structures (Webb et al. 2009) and filamentary isophote area, in order to cover LABs with asymmetric structures. For example, cold stream models predicted that LABs have asymmetric, long and thin filamentary structures. Goerdt et al. (2010) and Faucher-Giguere et al. (2010). An alternative quantity for the LAB selection may be \(Ly\alpha\) luminosity. However, the \(Ly\alpha\) luminosity could be dominated by a bright central core, such as starbursts in the central galaxy and AGN.

Six out of the 14 LABs have been spectroscopically confirmed by previous surveys (Steidel et al. 2000; Barger et al. 2002; Chapman et al. 2001; Basu-Zych & Scharf 2004; Geach et al. 2009).

3 RESULTS

Object detection and photometry are performed using the double image mode of SExtractor version 2.5.0 (Bertin & Arnouts 1996). For source detection, we use smoothed \(NB\) images with Gaussian kernels to match their seeing to a FWHM of 1.4 arcsec in order to slightly increase the sensitivities for diffuse extended sources and to make all the images the same seeing size. We use the same detection threshold (DETECT-THRESH) of 1.4 × 10\(^{-18}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) (or 28.5 mag arcsec\(^{-2}\)) for all the 12 fields.

The total survey area after masking low S/N regions and bright stars is 2.12 square degrees and the survey volume is 1.6 × 10\(^6\) Mpc\(^3\). This is 12 times larger than the survey area of Matsuda et al. (2004) and 100 times larger than that of Steidel et al. (2000). The 1-\(\sigma\) surface brightness limits of the \(N_b\) images are 0.7 – 1.2 × 10\(^{-18}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\).
Figure 3. Sky distribution of the 14 giant LABs and smoothed density maps of ∼ 2000 compact LAEs at z ∼ 3.09. In the left panel (a), the small black box indicates SSA22a field by [Steidel et al. 2000, S00] and the dashed box indicates SSA22-Sb1 by [Matsuda et al. 2004, M04]. The thick bars show the angular scale of 20 comoving Mpc at z = 3.1. The blue squares and red circles indicate the giant LABs without QSO and with QSO, respectively. The contours represent LAE overdensity, δLAE = (n − n)/n = 0, 1, 2, 3, 4, 5, and 6.

Figure 4. Filamentarity of the 14 giant LABs as a function of the overdensity of LAEs. The blue squares and red circles indicate giant LABs without QSO and with QSO, respectively. The error bars show 1-σ uncertainties. The filamentarity of the LABs shows a weak anti-correlation with the overdensity of LAEs.
the results do not change significantly if we use isophotal area for the LAB selection, suggesting that the correlation is not due to the selection method.

4 DISCUSSION AND CONCLUSIONS

Based on deep, wide-field Ly$\alpha$ imaging, we construct a sample of 14 giant LAB candidates at $z = 3.1$ from a volume of $1.6 \times 10^6$ comoving Mpc$^3$. This is the largest sample of giant LABs and triples the number of known LABs over 100 kpc. Our giant LAB sample shows a wide variety of Ly$\alpha$ morphologies and resides not only in overdense environments, as derived from LAEs, but also in lower dense environments. We find a possible hint for "morphology-density" relation of the LABs: the Ly$\alpha$ filamentarity seems to differ as a function of the local density environments.

How can we interpret this possible morphology-density relation of the LABs? The Ly$\alpha$ morphology may relate to the formation mechanisms of LABs. According to recent numerical simulations, more filamentary LABs may be good candidates for cold gas accretion from the surrounding IGM (Goerdt et al. 2010, Faucher-Giguere et al. 2010). Although direct evidence for such gas inflows is not found around star-forming galaxies at $z \sim 2$ (Steidel et al. 2011), recent studies of the metallicity of star-forming galaxies from low- to high-redshifts indicate that gas inflows may still be dominant in the field environment at $z \geq 3$ (Mannucci et al. 2011). More circular LABs may relate to large-scale gas outflows, which are driven by intense starbursts and/or AGN activities (Mori & Umemura 2006). At high-redshift, starformation and AGN activities in overdense environments are known to be several times higher than those in the field environments (e.g., Smail et al. 2003). Future spectroscopic and multi-wavelength follow-up observations would enable us to investigate the gas dynamics and the variations of the star-formation and AGN activities in giant LABs as a function of the environments and to test the interpretations.

ACKNOWLEDGMENTS

We thank an anonymous referee for helpful comments which significantly improved the clarity of this paper. We thank Ian Smail for help and useful discussions. YM acknowledges support from STFC. This research is supported in part by the Grant-in-Aid 20540224 for Scientific Research of the Ministry of Education, Science, Culture, and Sports in Japan.

REFERENCES

Alexander D. M., et al., 2003, AJ, 126, 539
Barger A. J., Cowie L. L., Brandt W. N., Capak P., Garnire G. P., Hornschemeier A. E., Steffen A. T., Wehner E. H., 2002, AJ, 124, 1839
Basu-Zych A., Scharf C., 2004, ApJ, 615, L85
Bertin, E., & Arnouts, S. 1996, A&A, 117, 393
Capak P., et al., 2004, AJ, 127, 180
Chapman S. C., Lewis G. F., Scott D., Richards E., Borys C., Steidel C. C., Adelberger K. L., Shapley A. E., 2001, ApJ, 548, L17
Condon J. J., Cotton W. D., Greisen E. W., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J., 1998, AJ, 115, 1693
Curti R. M., et al., 2003, The IRSA 2MASS All-Sky Point Source Catalog, NASA/IPAC Infrared Science Archive, http://irsa.ipac.caltech.edu/applications/Gator/
Dey A., et al., 2005, ApJ, 629, 654
Dijkstra M., Loeb A., 2009, MNRAS, 400, 1109
Faucher-Giguere C. -., Keres D., Dijkstra M., Hernquist L., Zaldarriaga M., 2010, arXiv, arXiv:1005.3041
Francis P. J., et al., 1996, ApJ, 457, 490
Furlanetto S. R., Schaye J., Springel V., Hernquist L., 2005, ApJ, 622, 7
Furusawa H., et al., 2008, ApJS, 176, 1
Geach J. E., et al., 2005, MNRAS, 363, 1309
Geach J. E., et al., 2009, ApJ, 700, 1
Goerdt T., Dekel A., Sternberg A., Ceverino D., Teyssier R., Primack J. R., 2010, MNRAS, 933
Greve T. R., Stern D., Ivison R. J., De Breuck C., Kovacs A., Bertoldi F., 2007, MNRAS, 382, 48
Haiman Z., Spaans M., Quataert E., 2000, ApJ, 537, L5
Hayashino T., et al., 2004, AJ, 128, 2073
Iye M., et al., 2004, PASJ, 56, 381
Kashikawa N., et al., 2004, PASJ, 56, 1011
Keel W. C., Cohen S. H., Windhorst R. A., Waddington L., 1999, AJ, 118, 2547
Landolt A. U., 1992, AJ, 104, 340
Mannucci F., Cresci G., Maiolino R., Marconi A., Gnerucci A., 2010, arXiv, arXiv:1005.0036
Matsuda Y., et al., 2004, AJ, 128, 569
Matsuda Y., et al., 2005, ApJ, 634, L125
Matsuda Y., Yamada T., Hayashino T., Yamauchi R., Nakamura Y., 2006, ApJ, 640, L123
Matsuda Y., et al., 2009, MNRAS, 400, L66
Miyazaki S., et al., 2002, PASJ, 54, 833
Mori M., Umemura M., 2006, Natur, 440, 644
Nilsson K. K., Fynbo J. P. U., Moller P., Sommer-Larsen J., Ledoux C., 2006, A&A, 452, L23
Oke, J. B. 1990, AJ, 99, 1621
Ouchi M., et al., 2003, ApJ, 582, 60
Palunas P., Teplitz H. I., Francis P. J., Williger G. M., Woodgate B. E., 2004, ApJ, 602, 545
Prescott M. K. M., Kashikawa N., Dey A., Matsuda Y., 2008, ApJ, 678, L77
Prescott M. K. M., Dey A., Jannuzi B. T., 2009, ApJ, 702, 554
Schlegel D. J., Finkbeiner D. P., Davis M., 1998, ApJ, 500, 525
Shen Y., et al., 2007, AJ, 133, 2222
Shimizu I., Umemura M., 2010, MNRAS, 406, 913
Smidt, Scharf C. A., Ivison R. J., Stevens J. A., Bower R. G., Dunlop J. S., 2003, ApJ, 599, 86
Smith D. J. B., Jarvis M. J., 2007, MNRAS, 378, L49
Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2000, ApJ, 532, 170
Steidel C. C., Adelberger K. L., Shapley A. E., Pettini M., Dickinson M., Giavalisco M., 2003, ApJ, 592, 728
Steidel C. C., Erb D. K., Shapley A. E., Pettini M., Reddy N. A., Bogosavljević M., Rudie G. C., Rakic O., 2010, arXiv
Taniguchi Y., Shioya Y., 2000, ApJ, 532, L13
Yagi M., Kashikawa N., Sekiguchi M., Doi M., Yasuda N.,
Shimasaku K., Okamura S., 2002, AJ, 123, 66
Yang Y., Zabludoff A., Tremonti C., Eisenstein D., Davé
R., 2009, ApJ, 693, 1579
Webb T. M. A., Yamada T., Huang J.-S., Ashby M. L. N.,
Matsuda Y., Egami E., Gonzalez M., Hayashimo T., 2009,
ApJ, 692, 1561