Ionizing Radiation from Galaxies at z=3 through Wide-Field Narrow-Band Imaging

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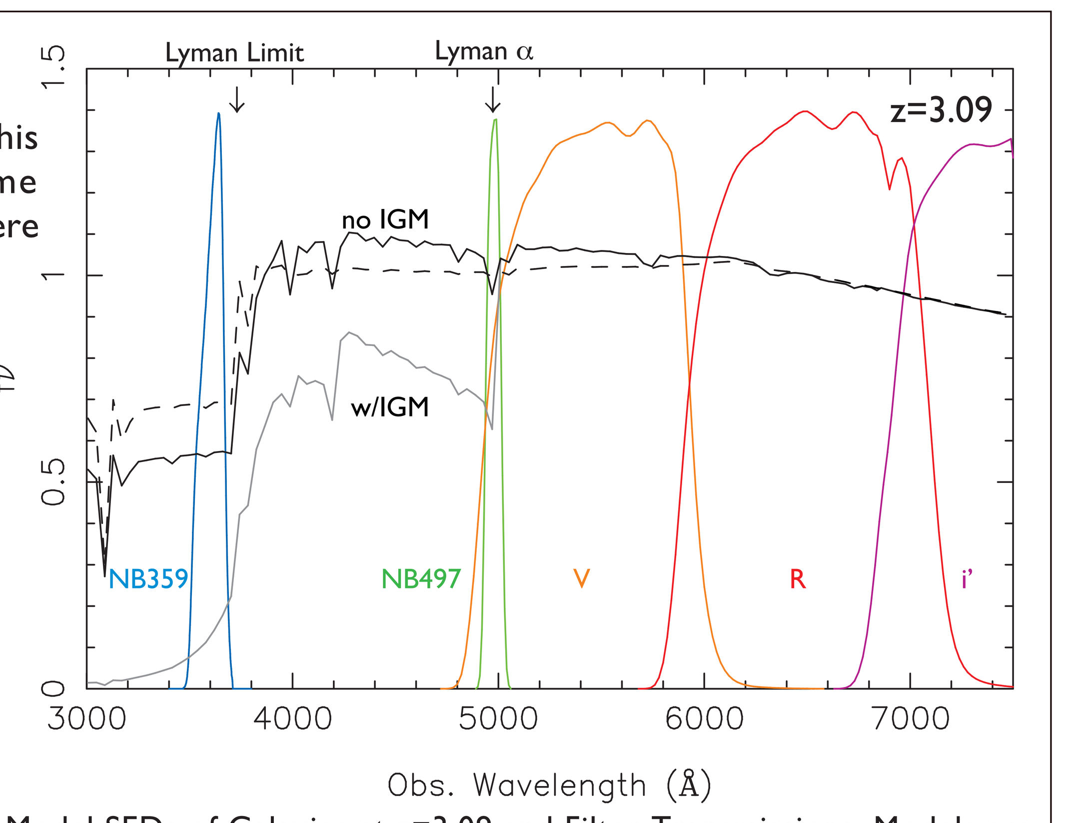
Knowing the amount of ionizing photons from young star-forming galaxies is of particular importance to understanding the reionization process. Here we report initial results of Subaru/Suprime-Cam deep imaging observation with a special narrow-band filter to optimally trace ionizing radiation from galaxies at z>3. The unique wide field-of-view of Suprime-Cam enabled us to search for ionizing photons from 198 galaxies with spectroscopically measured redshifts z~3.1. We detected ionizing radiation from 7 Lyman break galaxies (LBGs), as well as from 10 Ly-a emitter (LAE) candidates. Some of the detected galaxies show significant offsets of ionizing radiation from non-ionizing UV emission. As an average of the 7 detected LBGs, the observed flux density ratio of non-ionizing UV to ionizing radiation is estimated to be 4.9, which is smaller than values expected from population synthesis models with a standard Salpeter initial mass function (IMF) and dust attenuation. This implies an intrinsically bluer spectral energy distribution, e.g, that produced by a top-heavy IMF, for these LBGs. The observed flux density ratios of the detected LAEs are even smaller than those expected from a top-heavy IMF and QSOs if they are truly at z~3.1. We find that the average escape fraction of ionizing photons for the detected LBGs should be higher than 15%.

Observations

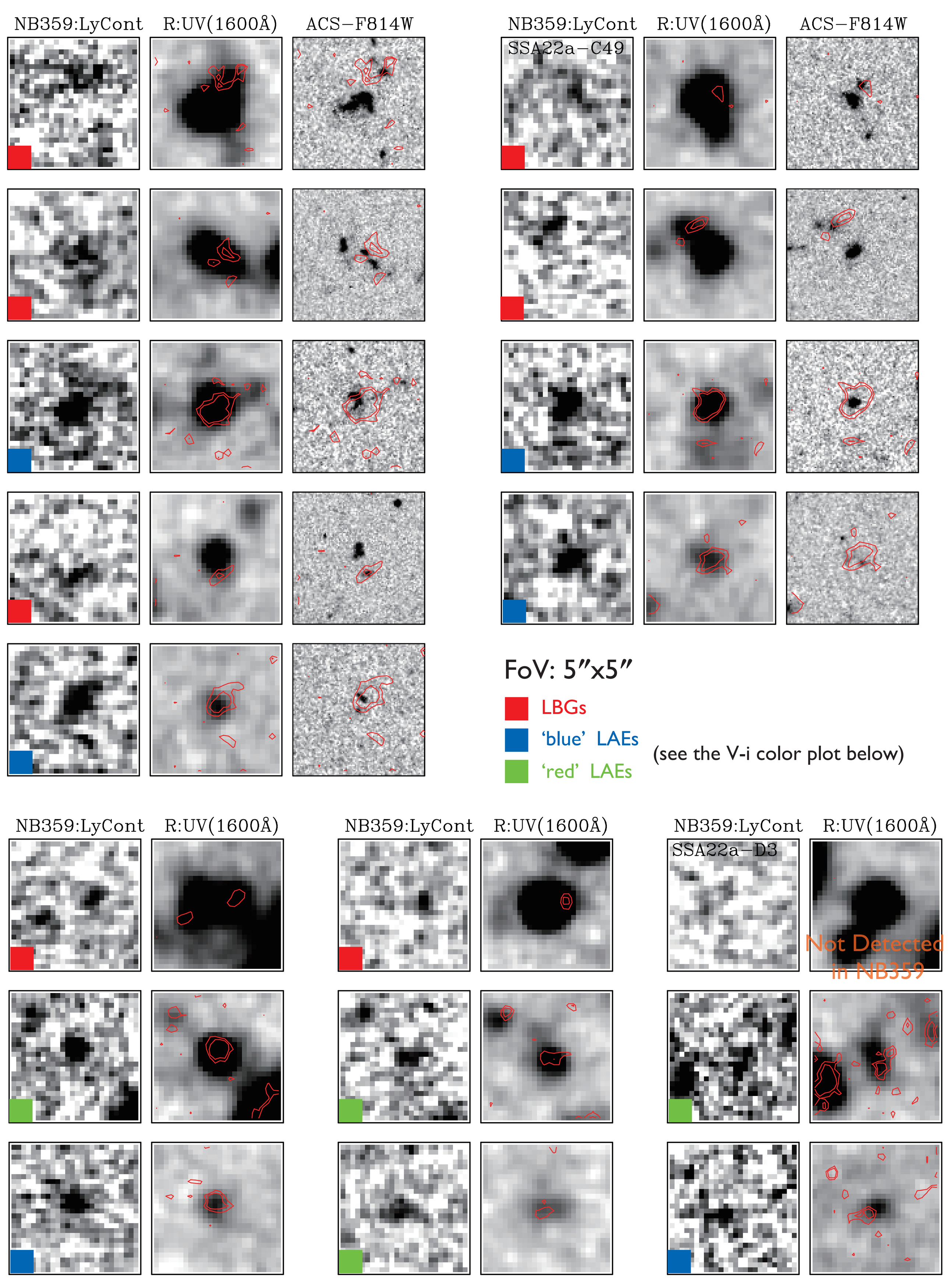
We created a special narrow-band filter NB359 for this project. It is designed to optimally trace rest-frame ~900A for galaxies at z=3.09. The FWHM is 15nm. There is no red leak more than 0.01% for 0.4um to 1.2um.

Subaru Telescope, Mauna Kea, Hawaii
Suprime-Cam: 34′ x 27′ FOV
Filter: Special Narrow-band Filter NB359
10-14 Sept. 2007. Seeing: 0.″5-0.″9 @ 0.36μm
Total On-source Exposure Time: 22.5 hrs
Limiting Mag.: 27.33 AB (3σ, 1.2″ ϕ)



Model SEDs of Galaxies at z=3.09 and Filter Transmissions. Models are generated with Starburst99, metallicity Z=4e-4, age=0. No Dust Attenuation. Normalized at 6500Å. Solid Lines: Salpeter IMF (0.1-120 Msun). With and without IGM attenuation. Dashed line: Top-heavy IMF (slope=-1.0), without IGM attenuaion. NB359 is the filter used to trace Lyman continuum. NB497 is the filter used to select Lyα emitters at z~3.09.

Results - Detections of Lyman Continuum



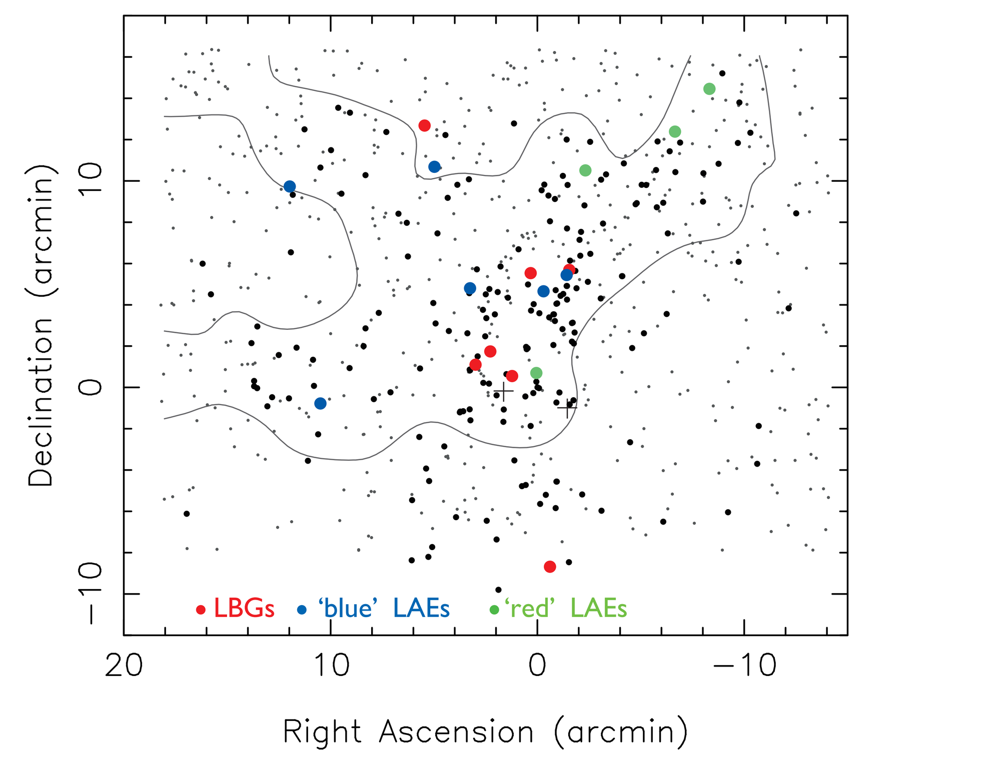
Among the 198 galaxies with spectroscopic redshift larger than 3.0, we detected Lyman continua from 16 objects (6 LBGs and 10 LAE candidates) at >3σ level. Also, SSA22a-C49 which has been detected spectroscopically by Shapley et al.(2006) is also detected at 2.96σ. We include this object in the list of detected galaxies. On the other hand, SSA22a-D3, another object detected by Shapley et al. (2006) is not detected in our NB359 image (see the lower-left figure).

There are 9 galaxies (5 LBGs and 4 LAEs) for those high resolution HST/ACS F814W images are available (Abraham et al. 2007; Geach et al. 2007). For them postage stamp images in NB359 (Lyman continuum), Suprime-Cam R-band and ACS F814W (both are non-ionizing UV) are shown. For the remaining 8 galaxies as well as SSA22a-D3, Suprime-Cam NB359 and R-band images are presented. FoV is 5″x5″. In R-band and F814W images 2σ and 3σ contours of NB359 are overplotted.

Many of the detected Lyman continua (especially from LBGs) show significant positional offsets from the R-band image (i.e., non-ionizing UV emission). HST/ACS images indicate that Lyman continuum associates with a sub-component of LBGs, and is not emitted from the luminous central part.

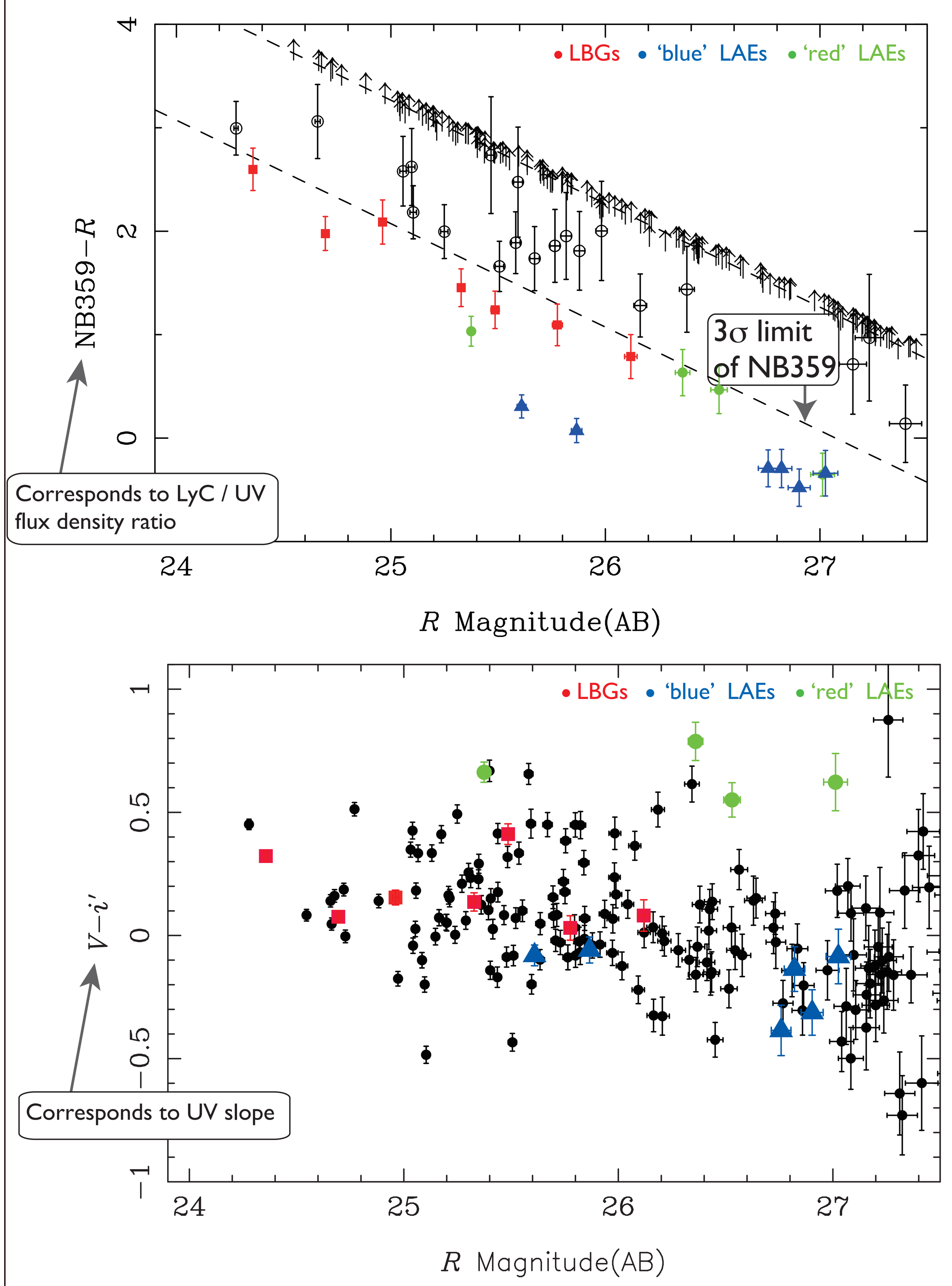
On the possibility of foreground contamination: We roughly estimated the probability of foreground contamination based on the U-band number counts and on the assumption that the spatial distribution of foreground sources is purely random. Each of 198 spectroscopic sample galaxies has ~0.6% chance of such foreground contamination. Thus we expect one or two foreground contamination, but it would be difficult to imagine that all 17 detections could be due to foreground contamination.

Spatial Distribution

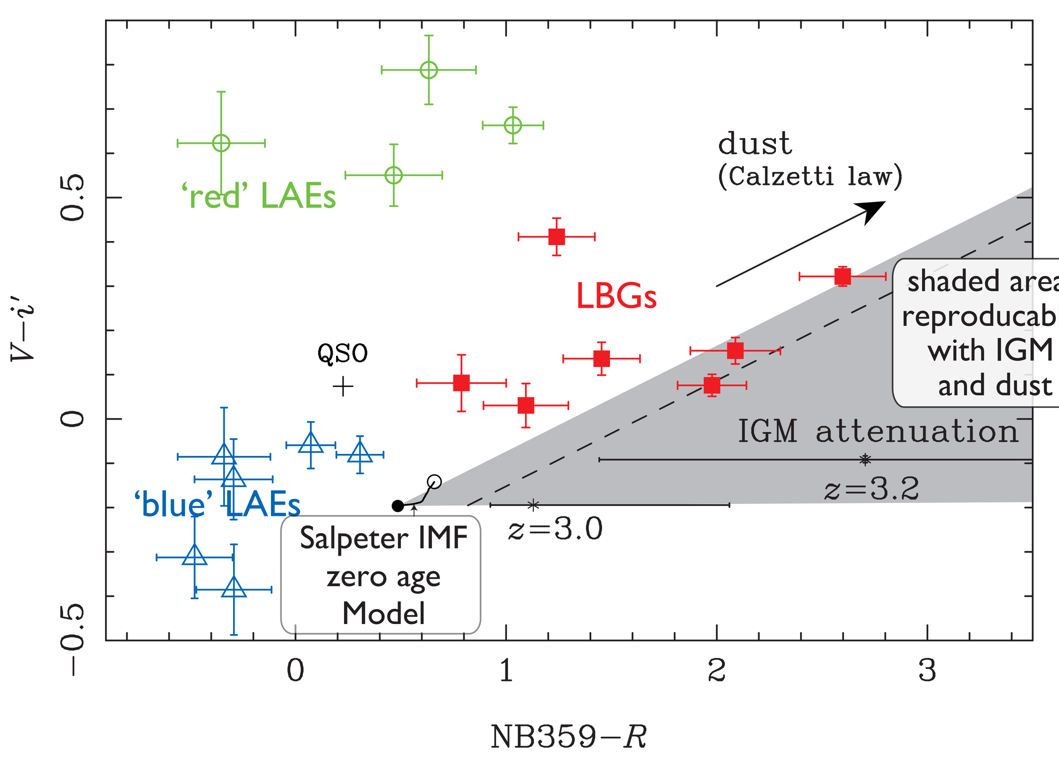


The 17 galaxies detected in NB359 (i.e., Lyman continuum) are shown in red (LBGs), blue and green (LAEs divided into two classes by UV slope, see color plots below) circles. Other 182 spectroscopically confirmed galaxies at z>3 are plotted with black circles. LAEs and Ly-α blobs selected by narrow-band imaging (Hayashino et al. 2004; Matsuda et al. 2004) but no spectroscopic confirmation are shown as dots. The high-density region of LAEs defined by Matsuda et al. (2004) is indicated with curves.

Color-Magnitude Distributions



Implications - Very Blue SED



NB359-R and V-i′ colors of 17 Lyman Continuum (LyC) detected galaxies are plotted. Colors of model galaxies with the Salpeter IMF (0.1-120 Msun), Z=1e-4, zero age, and no IGM and dust attenuation at z=3.0 (filled circle) and z=3.3 (open circle) are connected with a solid line. Colors indicated by a shaded area can be reproduced by considering Calzetti dust attenuation law and IGM attenuation (Inoue and Iwata 2008). The dashed line indicates IGM attenuation with the least 1% probability for z=3.0 and z=3.2; 99% slightlines should make object spectrum redder than this line in NB359-R. Four LBGs have NB359-R colors bluer than the model colors without IGM attenuation. This result strongly suggests that intrinsic SED of LBGs are bluer than the model SED considered here. Since this model has the bluest SED among the models with the Salpeter IMF, IMF of LBGs would be top-heavy. Another possibility is that dust property may be different from the present assumption. The LAEs, especially 'blue' LAEs have much bluer NB359-R colors. Note however, that NB359-R color of a single massive star at z=3.09 (based on the model spectra by Castelli and Kurucz) can be less than -1.0. Thus colors of LAEs are not physically impossible, although their colors are surprisingly blue.

Constraints on Escape Fraction

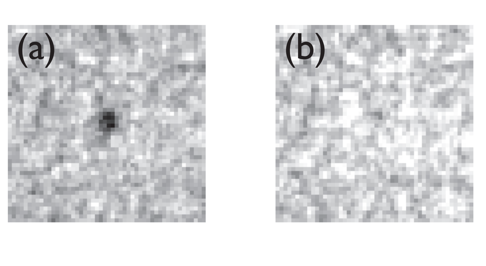
Average Escape Fraction of 7 LBGs detected in Lyman Continuum

The relative escape fraction is defined as (Steidel et al. 2001):

$$f_{esc,rel} = (f_{1500}/f_{900})_{int}/(f_{1500}/f_{900})_{obs}\exp(\tau_{IGM,900})$$

where $(f_{1500}/f_{900})_{int}$ and $(f_{1500}/f_{900})_{obs}$ are the intrinsic and observed UV to Lyman continuum (LyC) flux density ratios, respectively, and $\tau_{IGM,900}$ is the IGM optical depth for LyC along the line of sight. We assume $(f_{1500}/f_{900})_{int}$=3.0, following previous studies. The average $(f_{1500}/f_{900})_{obs}$ for 7 LBGs is 4.9±2.9. If we consider the case without IGM attenuation, $f_{esc,rel}$=0.61, which is a lower limit of the relative escape fraction. Under the assumption of E(B-V)=0.15, which would be reasonable for their UV slope (see V-i′ colors above), we obtain the lower limit of the escape fraction to be 0.15. Correction for the IGM opacity with 1% probability (very rare transparent sightlines) and median opacity yield the escape fraction to be 0.20 and 0.26, respectively. Thus we conclude that for LBGs with detected LyC emission the average escape fraction is highly likely to be higher than 0.20. Note that in the bluest Salpeter model described above $(f_{1500}/f_{900})_{int}$ is 1.82, and in such cases the escape fraction estimates become x0.6.

Average Escape Fraction of Galaxies at z~3, from Composite Images (*preliminary*)



(a) Composite NB359(=LyC) image of 471 galaxies with 23.0<R<26.5, including LBGs at z>3.06 and LAEs.
(b) Same as (a) but without galaxies detected in NB359 at >3σ. The number of galaxies used is 413.

Average escape fraction for galaxies at z~3 in the SSA22 field can be estimated from the composite NB359 image of galaxies. From our sample galaxies we select galaxies with spectroscopic redshifts between 3.06 and 3.2, as well as LAEs without spectroscopy. The number of galaxies are 471, which does not include known AGNs. A signal is detected at 6.4σ, which corresponds to 0.16 μJy. A composite image for R-band is created in the same way, and we obtain 1.41 μJy. If we assume the average IGM opacity at z=3 and $(f_{1500}/f_{900})_{int}$=3.0, the average $f_{esc,rel}$=0.60. Under the assumption of E(B-V)=0.15, escape fraction is 0.15. On the other hand, if we exclude galaxies detected >3σ in NB359, the signal in a composite of the remaining 413 galaxies is only ~1σ level. The 3σ upper limit of $f_{esc,rel}$=0.28, and this smaller value compared to 0.60 (for all galaxies) may suggest the diversity of escape fraction for galaxies at z~3.

References:
Iwata et al. 2008, submitted to ApJL (arXiv:0805.4012); Inoue and Iwata 2008, MNRAS in press (arXiv:0804.2951); Inoue et al. 2005, A&A 435, 471; Matsuda et al. 2004, AJ 128, 569; Hayashino et al. 2004, AJ 128, 2037; Abraham et al. 2007, ApJ 669, 184; Geach et al. 2007, ApJ 655, L9; Steidel et al. 2001, ApJ 546, 665; Shapley et al. 2006, ApJ 651, 688; Siana et al. 2007, ApJ 668, 62