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Multifrequency Observations of High-z Sources

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The high redshift Universe has been the subject of intense studies in the past few years. This has been possible thanks to the discovery of high redshift sources with very large telescopes. The principal methods of discovering these sources have been either using the drop-out technique or through the use of very narrow band filters. The first approach has given large quantities of the so called, Lyman Break Galaxies (LBG), out to redshift of nearly 10. The later technique has produced the so called Lyman Emitters (LAE), characterized by a prominent Lyman alfa emission line. Irrespective of the technique used for their discovery, spectroscopy is always important to properly characterize these high-z sources. Moreover, multi-band observations are always important to improve the understanding of these sources. In this talk I discuss two LAEs, that have been confirmed spectroscopically, with the GTC. These LAEs are a close pair, having similar redshifts and being very close in the plane of the sky. Fits to the SEDs of these sources have provided masses, star formation rates, extinction values and ages for their stellar populations. It has however been impossible to fit the SEDs of these sources with just one single stellar population. This comes mostly from the addition of data from the IR Spitzer bands. Only after the addition of these data has the proper nature of these galaxies been revealed.

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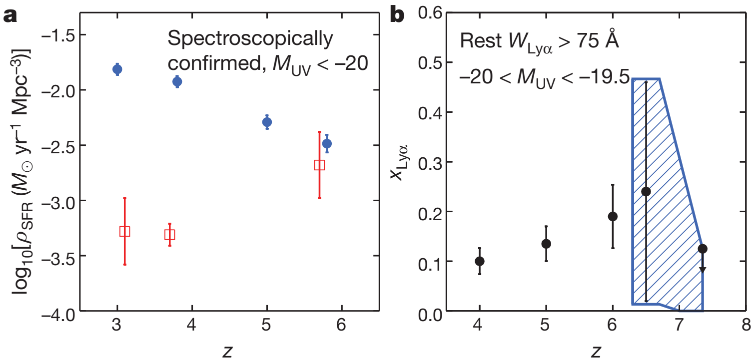

Figure 1: The different behavior of LAEs and LBGs. From Robertson et al. 2010 Blue dots, LBGs, red dots LAEs. Y axis: Left panel, density of Star Formation Rate, right panel, Fraction of LAES

1. Introduction

The study of the high-z Universe has received much attention in the last few years. This has been due to the availability of large telescopes with sensitive instruments. The study of the high-z Universe has been done mostly through the study of 1) galaxies exhibiting Lyman line emission redshifted to the optical-IR and the near IR, the so called Lyman Emitters (LAE), and 2) galaxies showing a large drop in a given filter after being prominent in redder filters. These are the so called Lyman Break galaxies (LBG). While the LAEs show a prominent Lyman α line and typically no continuum, the LBGs do have a prominent UV rest frame continuum. Since the Lyα line is a resonant line, the LAEs are very prone to absorption by either dust or neutral hydrogen. So the relative fraction of LAEs and LBGs tell us much about the history of re-ionization of the Universe. Figure 1, taken from [4] showing the different behavior of LAEs and LBGs as a function of redshift. In panel **a** the number of LAEs increases with redshift as the universe has less and less dust at higher redshifts. With no changes in the Intergalactic Medium (IGM) one would expect more high-z LAEs. The abundance of LBGs is however decreasing in this same range. Beyond z $\sim$ 6, the number of LAEs should continue increasing as the abundance of dust in the early Universe should be negligible. Panel **b** in Fig1 shows however a strong decrease in the number of Lyα sources, a clear indication that the fraction of neutral gas beyond z $\sim$ 6 has increased, suppressing the Lyα line. A clear indication that the Universe was at last only partially ionized by z = 6, and probably still containing a large fraction of neutral hydrogen.

It can therefore be said that much of what is known today about the High-z Universe has come from different samples of both LAEs and LBGs, built with either large telescopes or the HST. However, after much has been learned about the global properties of the Universe, it is also important to study in more detail the sources that produced the ionization of the Universe, and the sources that were able to maintain the density of ionizing photons necessary to keep the universe ionized. This talk is in fact devoted to two of those sources, discovered as LAEs, that when studied in detail, adding multi-frequency data, showed very interesting behavior.

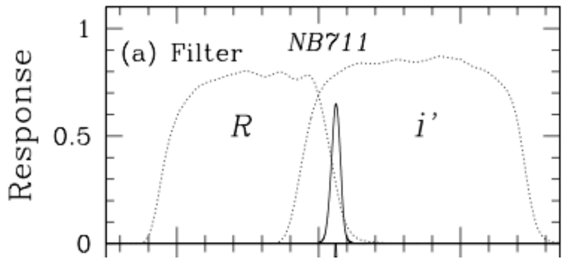

Figure 2: Sketch of the narrow band filter used by Ouchi in their pioneering work

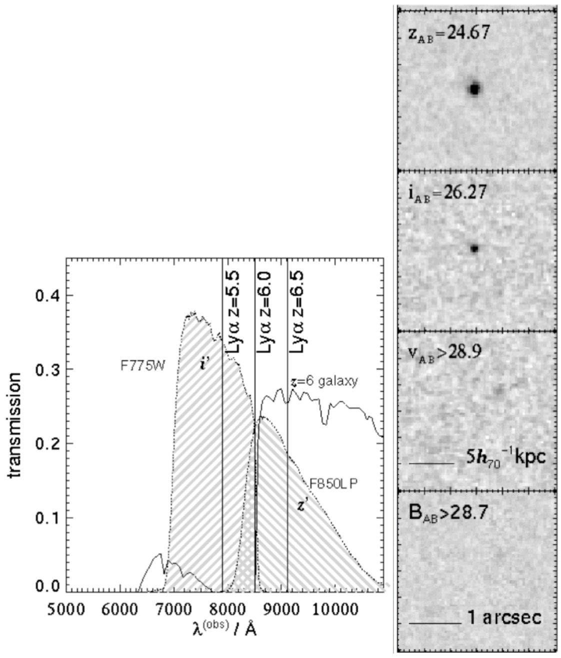

Figure 3: Left panel: Sketch of a typical LBG spectrum as seen by broad band filters. Note that the source would be seen by the z' and i' filters but not by the v' or b' filters. Right panel, images in four filters showing the drop in the v' filter.

2. Detecting LAEs and LBGs

LAEs have typically been discovered using narrow-band filters. These filters increase the contrast with the background and therefore facilitate the detection of faint emission line objects. The pioneering work was done with the SUBARU telescope and their sensitive camera *Suprime-Cam*, equipped with a filter centered at 721.6 nm, and FWHM of 7.3 nm (see Figure 2). With this filter they carried out the Subaru Deep field, detecting a large number of LAEs at a redshift of $\sim$ 4.86. The selection of the sources is typically done through Color - magnitud diagrams combining the narrow band filter with normal broad band filters. In these color-magnitud diagrams it is easy to spot sources that emit in the narrow filter ([2]). By changing the central wavelength of the narrow band filter, it is possible to detect sources at any redshift of interest.

LBGs are however detected with normal broad band filters, looking for extreme colors. The

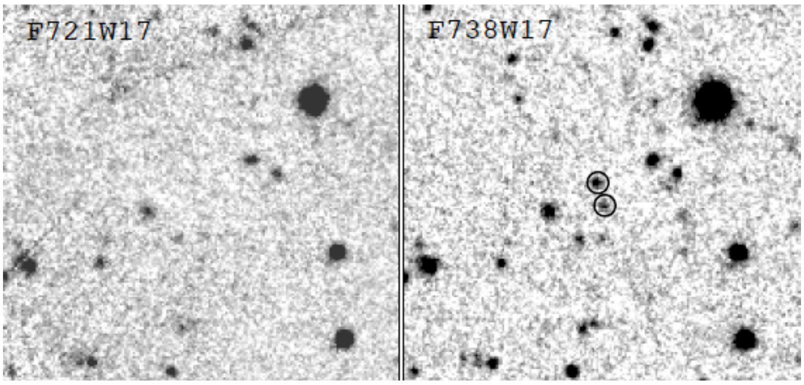

Figure 4: Right panel: The two sources marked are easily seen in this filter. Left panel: neither of the sources can be seen in this bluer filter.

technique is based on the sharp decrement that is seen beyond the Lyman limit, due to absorption of the ionizing photons by neutral hydrogen, while the strong rest frame UV continuum can be detected in redder broad band filters (Figure 2). Using these two techniques it has been possible to collect a large number of high-z galaxies from z $\sim$ 3 up to about z $\sim$ 10. The z $\leq$ 10 sources have been discovered with the WFC3 IR camera on board the HST. Their confirmation when available, comes mostly from the Keck/MOSFIRE (*e.g.* [3] and references therein).

3. Using SHARDS to detect high-z galaxies

We have used the ESO/GTC SHARDS survey to detect high redshift sources. SHARDS is a survey of the GOODS North field in 25 medium band filters. The sensitivity of this survey is 26.5 AB magnitude (3σ) in all filters. For more information about SHARDS please visit http://guaix.fis.ucm.es/~pgperez/SHARDS. Although SHARDS was motivated for studying the evolution of red galaxies up to z = 2.5, it can be used for our purpose of detecting high redshift galaxies from z $\sim$ 3 to about z = 6.5. By having the entire optical spectrum covered with medium band filters one can detect both LAEs and LBGs.

4. Two spectroscopically confirmed sources

In our search for high-z sources, we soon spotted two sources that met our criteria for showing Lyα emission. Essentially, we saw that both sources were clearly seen in filter SF738W17 while being absent in any bluer filters. Figure 4 shows the SF721F17 and the SF738W17 images. The two sources mentioned can easily be seen in the right panel of the figure. These two sources are also very close in the plane of sky. If they were Lyα sources their redshift would be close to z=5. It is therefore important to characterize spectroscopically these sources. So we applied for GTC time with the OSIRIS long slit spectrograph (at the time the multi-object capability had not been commissioned). So we performed spectroscopy of the two sources, thus being able to confirm the Lyα emission in both sources. Besides, the emission was in both cases at a redshift of 5.0722 and 5.0754, so we confirmed that not only were these sources close in the sky but also they are close in

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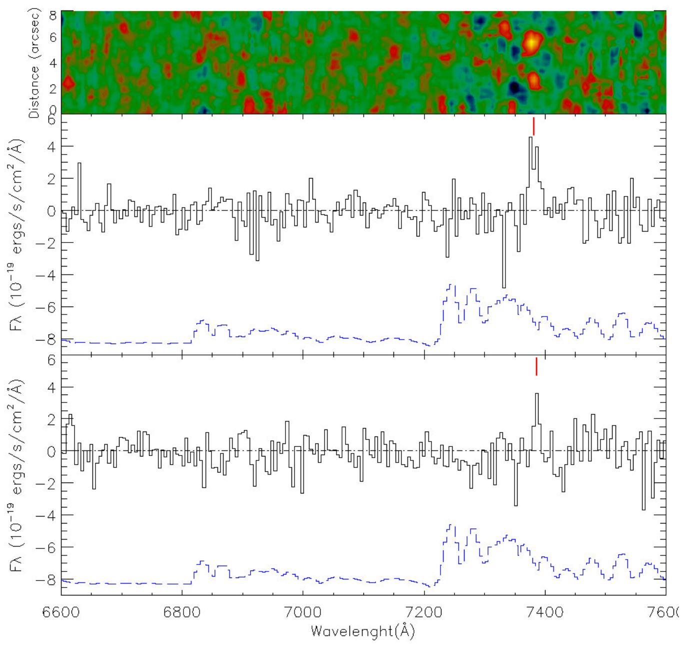

Figure 5: Upper panel: Two dimensional spectra of the two sources. Note the two blobs produced by the Lyα line. Middle and Bottom panels: spectra of the two sources.

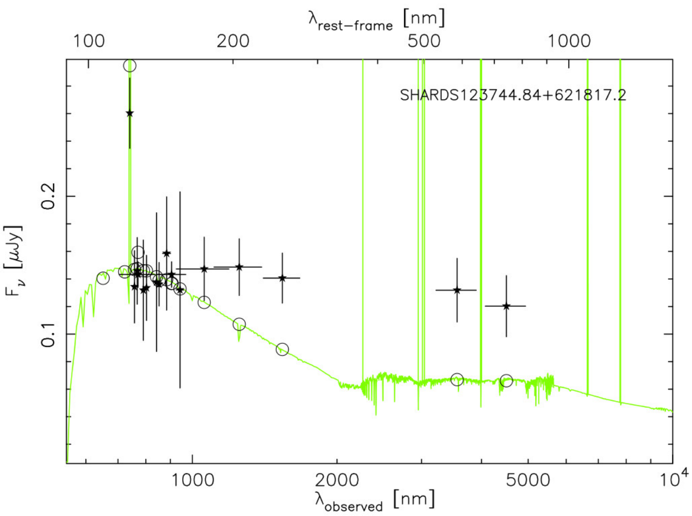

Figure 6: Model fit with a SSP for Obj2. Note the size of the deviation from a good fit starting at the optical-UV part of the spectrum, and becoming worse towards the rest-frame optical part of the spectrum. The contribution of nebular emission lines or the nebular continuum is negligible. A similar plot for Obj1 (not shown) leads to similar conclusions.

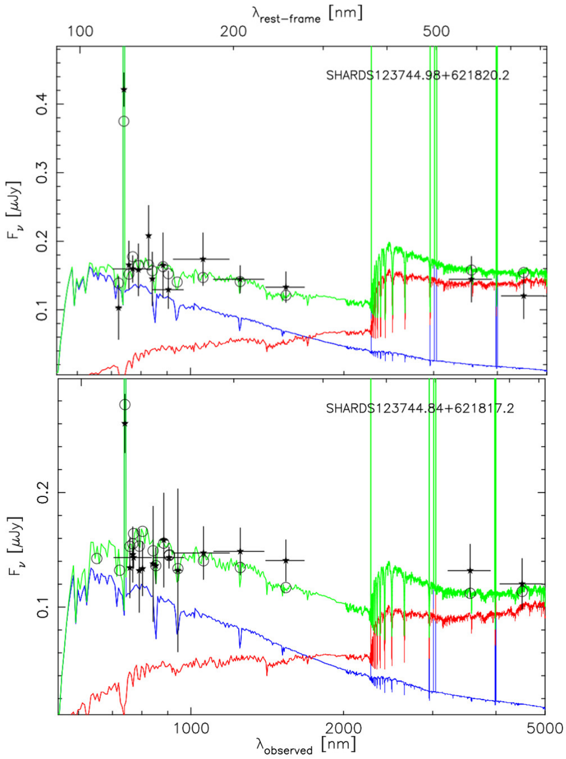

Figure 7: Spectral energy distributions including all the data available for the two sources. Filled stars show the observed data, while open circles show the fluxes derived from the best-fitting stellar population model. The spectro-photometric SEDs have been fitted to a two-component stellar population models. Blue shows the contribution of the youngest component, in red the oldest, and in green the resulting fit.

velocity space. Figure 5 shows the spectra of both sources. Note that in spite of the sky noise, the emission can be readily seen with very good signal to noise.

The SHARDS data, together with the spectral data, plus additional broad band data from Subaru, HST and Spitzer were used to build Spectral Energy Distributions of either of the sources. It is only with this larger set of data that the study of these two sources can be undertaken with confidence. Indeed, we can now fit any model of stellar populations. In our case we started fitting single population model from [1], including line and emission continuum from both H and Helium. We made different tests varying parameter like dust content, ages or metallicity, etc. It was impossible to reach any sensible result (see Figure 6). We were therefore forced to fit two distinct stellar populations. The important issue to note is that in both cases we were directed to fit two stellar populations. These were an old population that underwent a burst of star formation about 100 million year ago, and accounts for most of the mass from these galaxies. Plus, a younger population (2 Myr old) that would be responsible for the observed Lyman alpha emission. Figure 7 show the two-component stellar population fits for either of the sources.

5. Summary

We have studied two Lyα emitting sources discovered in the SHARDS survey. We have seen that only after considering near IR data (rest frame optical-IR) we have been able to perform an adequate fit to two stellar populations. With the UV rest frame continuum plus the Lyα line we would have seen only the recent burst of star formation. It is only the addition of multi-wavelength data that we have seen the need to account for an additional stellar population, that on top of it, it represents the bulk of the mass present in these two galaxies.

References

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[2] Ouchi, M., Shimasaku, K., Furusawa, H, et al. 2003, ApJ 582, 60

[3] Oesch, P.A., van Dokkum, P.G., Illingworth, G. D., et al. 2015, ApJ 804L, 30

[4] Robertson, B. E., Ellis, R. S., Dunlop, J. S., McLure, R. J. & Stark, D. P., 2010, Nature, 468, 49