Breaking Cosmic Dawn: The Faintest Galaxy Detected by the VLT

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Astronomers have been debating the origin of galaxies for centuries and the timeline of the evolution is now well established. However, despite the success of galaxy formation models, some questions remain largely unanswered. Chief among them is how the first galaxies formed. When the Universe was in a highly opaque state, these first galaxies most likely cleared the cosmic fog and broke the cosmic dawn. However, there are large uncertainties as to how this transition occurred and what the exact role of the first galaxies was. Using galaxy clusters as cosmic telescopes that magnify background objects, we were able to detect hydrogen emission from a galaxy at a redshift of $z = 6.740 \pm 0.003$ using FORS2 on the VLT. To date, this is the faintest galaxy with a successfully measured spectrum and as such an important beacon for cosmic dawn.

Cosmic dawn through cosmic telescopes

The cosmic Dark Ages are thought to have ended around 500 million years after the Big Bang when early light sources produced enough energetic photons to ionise the neutral hydrogen, making the Universe transparent to visible light. This era is referred to as reionisation and is also the era of the formation of the first galaxies. But when exactly did reionisation occur and how long did it last? What were the sources responsible for ionising the neutral gas? Was it the first galaxies? Now, for the first time, we can peer far enough into space to detect these galaxies spectroscopically and answer these questions.

Observations of galaxies at these early times are challenging, not only due to the large distance to these objects, but also due to their lower luminosity (galaxies had fewer stars when they first formed). The quest to discover the most distant (i.e., first) galaxies has advanced rapidly in the last decade. With the help of a galaxy cluster acting as a cosmic telescope and magnifying the background Universe, we have observed the faintest galaxy ever detected spectroscopically at these extremely large distances. It was detected using the FORS2 spectrograph on the Very Large Telescope (VLT). With an extremely long exposure time (16 hours on a mask, a total of 22 hours of observing time) and assisted by nature's own telescope (The Bullet Cluster) we were able to push to the limits of the light-gathering power of the VLT which allowed us to detect Lyman-α emission from this "normal" (i.e., not ultraluminous) galaxy (Bradač et al., 2012).

Beyond simple counting

Detection of high-redshift galaxies is performed by searching for the redshifted Lyman break using broadband photometry (Steidel et al., 1996). These so-called Lyman Break Galaxies (LBGs, see e.g., Vanzella et al., 2009) are the best studied and the largest sample of galaxies at redshifts $z > \sim 5$. One can identify $z \approx 5$ objects by their non-detection in the *V*-band and blueward: such objects are referred to as *V*-band dropouts. Similarly, objects at $z \approx 6$ are associated with *i*-band non-detection, $z \approx 7$–8 with *z*-band, and $z > \sim 8$ objects would be observed as *J*-band dropouts. Substantial progress has been made in detecting $z > \sim 7$ galaxies using the dropout technique (Steidel et al., 1996), both in blank fields (the Hubble Ultra-Deep Field [HUDF] and the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey [CANDELS]; e.g., Bouwens et al., 2012), and behind galaxy clusters (e.g., Hall et al., 2012). One of the most obvious limitations of the dropout technique, however, is that unambiguously confirming the object's redshift usually requires spectroscopic follow-up. This is hard to do for the typically faint high-*z* sources.

However much more important than the redshift confirmation, spectroscopy provides information on properties of the interstellar and intergalactic media (ISM and IGM). In particular, Lyman-α emission from sources close to the reionisation era is a valuable diagnostic, given that it is easily erased by neutral gas within and around galaxies. The observed strength of Ly-α in distant galaxies is a gauge of the time when reionisation was completed (Robertson et al., 2010). Furthermore, we expect Ly-α Emitters (LAEs) to be predominantly dust-free galaxies; hence their numbers should increase with redshift until the state of the IGM becomes neutral, at which point their numbers should decline.

A powerful way to detect emission lines from faint sources is to use galaxy clusters as cosmic telescopes (e.g., Treu, [2010] for a recent review). Gravitational lensing magnifies solid angles while preserving colours and surface brightness. Thus, sources appear brighter than in the absence of lensing. The advantages of cosmic telescopes are that we can probe deeper (due to magnification), sources are practically always enlarged and identification is further eased if sources are multiply imaged. Typically, one can gain several magnitudes of magnification, thus enabling the study of intrinsically lower luminosity galaxies that we would otherwise not be able to detect with even the largest of current telescopes.

The combined power of VLT and the "Silver Bullet"

Our targets were selected from deep Advanced Camera for Surveys (ACS) and Wide Field Camera 3 (WFC3) data, both on the Hubble Space Telescope (HST). Ten z-band dropouts were found by Hall et al. (2012). The aim of the VLT programme 088.A-0542 (PI Bradač) was to target all these extraordinary targets with the FORS2 spectrograph. Ordinarily the hope of detecting any of these sources even with a programme of 22 hours would be impossible, as their intrinsic magnitudes are $H > 27$ AB mag. However with the help of magnification from the Bullet Cluster, which is one of the best cosmic telescopes (due to its large mass and elongation, the magnifications are large), the observed magnitudes of these ten sources are $H = 25–27$ AB mag. Of course, this does not make the observing easy *per se*!

Out of the ten z-band dropout candidates targeted, we detected an emission line at 9412 Å with 5σ significance (see Figure 1) in one target. The line is detected in two different FORS2 masks and is broader than cosmic rays or residuals due to sky subtraction; hence we are confident that the line is not an artefact (see Figure 2). No other emission lines are detected in the spectrum (7700–10000 Å); if the object were at lower redshift one would have expected detections of several lines. Based on this lack of other lines and on the spectral energy distribution fit using imaging, we exclude other alternative explanations and conclude that the line is most likely Ly-α at $z = 6.740 \pm 0.003$.

Breaking cosmic dawn

While this work presents only a single spectroscopic detection at $z > 6.5$, it nonetheless probes a very important region of parameter space. The intrinsic (unlensed) line flux of this object is ~ 2–3 times fainter than the, until now, faintest spectroscopic detection of an LAE at $z \sim 7$ (Schenker et al., 2012). Its intrinsic H(160W)-band magnitude is $m^{int}_{H(160W)} = 27.57 \pm 0.17$, corresponding to an intrinsic luminosity of 0.5 L^* at this redshift (see Table 1).

But more important than the record breaking is the fact that these sources are excellent beacons of cosmic

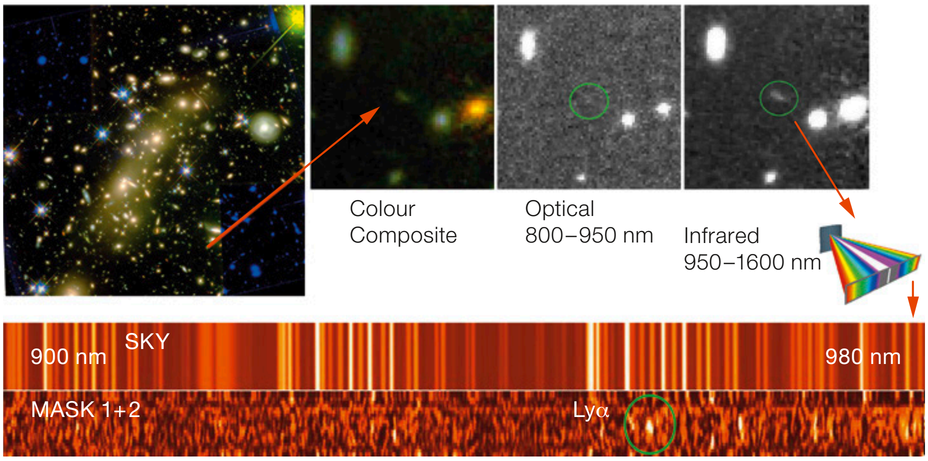

Figure 1. A distant source observed from when the Universe was less than 10 % of its current age. The object was found behind the Bullet Cluster. The top row shows an image of the cluster (from HST and WFC3), and a zoom-in on the source in a colour composite from an optical image and an infrared image. The bottom row shows a confirmation spectrum (from FORS2) of the object (sky emission above, object spectrum with Ly-α emission below).

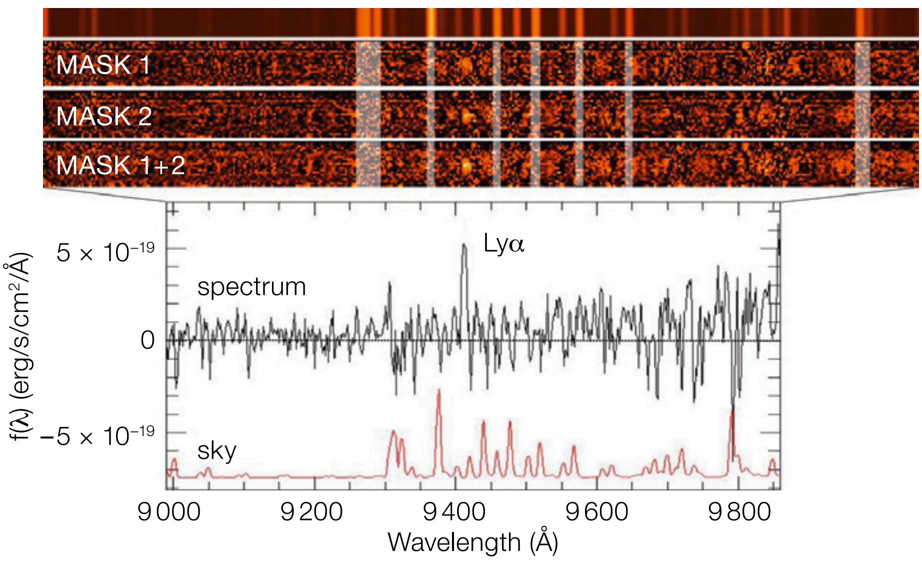

Figure 2. Upper: 2-D spectrum of the dropout galaxy (sky emission above, spectra from individual masks below). Lower: 1-D spectrum of the object. The sky spectrum has been rescaled by a factor of 300 and offset for display purposes, and the regions where skylines are more intense have been marked with transparent vertical bars. Strong residuals in the sky subtraction are evident and correspond to the more intense sky lines. Note that the detected line is broader than residuals of sky subtraction, confirming the reality of the feature.

reionisation. Measuring the rest frame equivalent width (EW) distribution of LAEs as a function of redshift and luminosity is a powerful tool to study reionisation. The EW distribution changes with redshift and source luminosity. Simulations suggest that reionisation is the key factor driving this trend (Dayal & Ferrara, 2012), because, unlike continuum photons, the Ly-α photons that escape the galactic environment are attenuated by the neutral hydrogen in the IGM. With a measurement of the EW distribution in LAEs we can therefore help distinguish between effects of ISM dust and neutral IGM and study the epoch of reionisation (see also Treu et al., 2012).

Our source is the faintest (in line flux) detected thus far and is only the second firm spectroscopic detection of a sub-L^* source at $z > 6.5$ (the other example is also a lensed galaxy at $z = 7.045$ discovered by Schenker et al. [2012]).

R.A.	104.63015
Dec.	−55.970482
m_{H160W}	26.37 ± 0.16
m_{J110W}	26.5 ± 0.3
$(J_{110W} - H_{160W})$	0.10 ± 0.15
$(z_{850LP} - J_{110W})$	1.57 ± 0.68
m_{V606}[a]	> 28.75 (t_{exp} = 2336s)
m_{i775W}	> 28.60 (t_{exp} = 10150s)
m_{I814W}	> 29.00 (t_{exp} = 4480s)
m_{K_s}	> 26.65 (t_{exp} = 3.75hr)
μ	3.0 ± 0.2
$m^{int}_{H(160W)}$	$27.57^{+0.17}_{-0.17}$
λ	9412 Å
z	6.740 ± 0.003
f^b	(0.7 ± 0.1 ± 0.3) × 10^{-17} erg/s/cm^2
$f_{\lambda,c}$	$3.3^{+1.0}_{-0.8}$ × 10^{-20} erg/s/cm^2/Å
f^{int}	(0.23 ± 0.03 ± 0.10 ± 0.02) × 10^{-17} erg/s/cm^2
$f^{int}_{\lambda,c}$	$1.1^{+0.4}_{-0.3}$ × 10^{-20} erg/s/cm^2/Å
W_{rest}(Ly-α)	30^{+12}_{-21} Å

Table 1. Imaging and spectroscopic properties of z_{850}-band dropout #10 from Hall et al. (2012).

Future is made bright by gravitational lensing

With future observations of dropout objects magnified by cosmic telescopes we will further increase the sample. As noted above, measuring the EW distribution of LAEs as a function of redshift and luminosity is a very powerful tool to study reionisation, because the latter is likely to be the key factor driving the trend of EW and luminosity. The main missing observational ingredient is a measurement of the EW distribution for both luminous and sub-L^* galaxies at the redshifts of reionisation; future surveys and facilities will achieve exactly that (e.g., X-shooter on VLT and the new spectrograph MOSFIRE on Keck; see McLean et al., 2010).

Perhaps even more importantly, however, we will also add the wavelength coverage to the observations. A first major improvement will be performed with deep Spitzer observations. There is a large Exploration Science programme approved for Spitzer Cycle 9. The programme (Spitzer UltRaFaint SUrvey - SURF'S Up: Cluster Lensing and Spitzer Extreme Imaging Reaching Out to $z > \sim 7$) will open up new parameter space and will allow us to study the properties (e.g., star formation rates and stellar masses) of a large number of galaxies at $z \sim 7$ for the first time. The presence (or absence) of an established stellar population will be measured in the targets and these findings will allow us to identify the dominant sources of the bulk of ionising photons necessary to drive reionisation.

Furthermore, in the local Universe, star formation is associated with molecular gas, and therefore to understand star formation properties we would like to trace molecules in the cold ISM of high redshift galaxies. ALMA is opening a new window for this endeavour. It is designed to trace molecular gas in galaxies up to $z \sim 5$ in the brightest cases. With the assistance of gravitational lensing, however, these limits can be pushed to the redshifts near reionisation. ALMA's incredible resolution can also be further improved with lensing, giving us access to the sub-kpc regime. This will allow us to characterise the spatial distribution and kinematics of the cold ISM in these extremely high redshift, but not ultra-luminous galaxies, something that would not have been possible without the help of gravitational lensing.

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