Bright Lyα Emitters at z∼9: constraints on the luminosity function *

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ABSTRACT

New results are presented, as part of the Hi-z Emission Line Survey (HiZELS), from the largest area survey to date (1.4 deg^2) for Lyα emitters (LAEs) at $z \sim 9$. The survey, which is primarily targeting Hα emitters at lower redshift, uses the Wide Field CAMera on UKIRT and a custom narrow-band filter in the J band and reaches a Lyα luminosity limit of $\sim 10^{43.8}$ erg s^{-1} over a co-moving volume of 1.1×10^6 Mpc^3 at $z = 8.96 \pm 0.06$. Only 2 potential candidates were found out of 1517 line emitters and those were rejected as LAEs after follow-up observations. The limit on bright Lyα emitters is improved by 3 orders of magnitude, consistent with negative evolution of the bright end of the Lyα luminosity function beyond $z \sim 6$. Combined with upper limits from smaller but deeper surveys, this rules out some of the most extreme models for high-redshift Lyα emitters. The potential contamination of future narrow-band Lyα surveys at $z > 7$ by galactic brown dwarf stars is also examined, leading to the conclusion that such contamination may well be significant for searches at $7.7 < z < 8.0$, $9.1 < z < 9.5$ and $11.7 < z < 12.2$.

Key words: galaxies: high-redshift, galaxies: luminosity function, cosmology: observations, galaxies: evolution.

1 INTRODUCTION

One of the most important questions in current extragalactic astronomy is "when did the first stars and galaxies form?". The detection and study of the most distant galaxies offers one of the greatest possible constraints on structure formation, allowing models of early galaxy formation and evolution to be tested, and either refined or refuted. Over the last decade, considerable manpower and telescope time has been dedicated towards this goal: galaxies have now been identified out to redshift $z \sim 7$, just 750 Myr after the Big Bang (Iye et al. 2006), and a Gamma Ray Burst (GRB) has been detected even further away, at $z \approx 8.3$ (Tanvir et al. 2009); the sample of very-high redshift galaxies is growing rapidly. Making the additional step out to redshifts of $z \sim 9$ is of the upmost importance because it not only offers much tighter constraints on the first star formation or AGN activity of the Universe, but also allows the re-

ionisation epoch of the Universe to be studied. As the mean fraction of neutral hydrogen in the intergalactic medium increases, the Lyα emission from these star forming galaxies will be strongly attenuated, leading to a sharp change in the Lyα luminosity function, although the precise details may depend upon the level of local ionization of the intergalactic medium by the star forming galaxies (e.g. Haiman & Cen 2005). Little evolution is seen in the Lyα luminosity function between $z \sim 3$ and $z \sim 6$, suggesting that the Universe was essentially fully ionized by $z = 6$ (e.g. Malhotra & Rhoads 2004; Ouchi et al. 2008), although some hints of evolution have been found at the bright end of the luminosity function beyond $z \sim 6$ (e.g. Kashikawa et al. 2006; Ota et al. 2008). Still, the re-ionisation epoch is widely believed to occur around $z \sim 9$, with this being supported by several models and observations; the latest results from the Cosmic Microwave Background (e.g. Dunkley et al. 2009; Komatsu et al. 2009) show that most of the re-ionisation occurred at $z = 10.9 \pm 1.4$ (1σ).

Presently, there are three relatively effective methods for searching for very distant galaxies: the broad-band drop-out technique, "blind" spectroscopic searches and narrow-band imaging surveys. The widely-used drop-out technique (pioneered at $z \sim 3$ by Steidel et al. 1996) requires very deep broad-band imaging, and

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can potentially identify $z > 7$ galaxies as z-band drop-outs (e.g. Bouwens et al. 2008; Richard et al. 2008). This method is efficient for identifying candidates, but requires detailed spectroscopic follow-up to confirm the candidates, especially to rule out contributions from other populations with large $z-J$ breaks, such as dusty or evolved $z \sim 2$ galaxies and ultra-cool galactic stars (e.g. McLure et al. 2006). Thus, while Richard et al. (2008) identified 2 good $z \sim 9 - 10$ candidates by taking advantage of the lensing magnification of a high mass cluster, their spectroscopic follow-up was inconclusive with no emission lines detected. "Blind" spectroscopic surveys can potentially provide spectra directly. They are always limited to very small areas, but Stark et al. (2007) targetted the critical lensing lines of clusters and were able to identify 6 potential $z \sim 9$ objects. Finally, the narrow-band imaging technique has the advantage of potentially probing very large volumes, but can only detect sources with fairly strong emission lines.

Narrow-band Lyα searches at slightly lower redshifts have been extremely successful in detecting and confirming emitters (e.g. Hu et al. 1998), including the detection of the most distant (spectroscopically confirmed) Lyα emitter to date at $z = 6.96$ (Iye et al. 2006). Since then, there have been attempts to detect Lyα at $z > 7$, and particularly at $z \sim 9$ (e.g. Willis & Courbin 2005; Cuby et al. 2007; Willis et al. 2008), some taking advantage of cluster lensing magnifications; all such studies have been unsuccessful to date, but have only surveyed very small areas (a few tens of square arcmins at most). With the advent of wide-field near-IR detectors, however, it is now possible to increase the sky areas studied by over 2 orders of magnitude and reach the regime where one can realistically expect to detect $z \sim 9$ objects. This is a key aim of, for example, the narrow-band component of the UltraVISTA Survey (c.f. Nilsson et al. 2007). It is also an aim of HiZELS, the Hi-Z Emission Line Survey (c.f. Geach et al. 2008; Sobral et al. 2009), that we are carrying out using the WFCAM instrument on the 3.8-m UK Infrared Telescope (UKIRT). HiZELS is using a set of existing and custom-made narrow-band filters in the J, H and K bands to detect emission line galaxies over ~ 5 square degrees of extragalactic sky; the narrow-band J filter (hereafter NB$_J$) is sensitive to Lyα at $z = 8.96$.

An $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ cosmology is used; magnitudes are given in the Vega system.

2   DATA AND SELECTION

Deep narrow-band J (NB$_J$ $\approx$ 21.6, 3σ, $F_{\mathrm{lim}} = 7.6 \times 10^{-17}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$) imaging was obtained across 1.4 deg^2 in the UKIRT Infrared Deep Sky Survey Ultra Deep Survey (UKIDSS UDS; Lawrence et al. 2007) and the Cosmological Evolution Survey (COSMOS; Scoville et al. 2007; Koekemoer et al. 2007) fields, both of which have a remarkable set of deep multi-wavelength data available – this resulted in the selection of 1517 potential line emitters. The NB$_J$ filter ($\lambda = 1.211 \pm 0.014\mu$m) is sensitive to Ly$\alpha$ emission at $z = 8.96 \pm 0.06$ (assuming a top-hat filter shape), corresponding to a probed co-moving volume of 1.07×10^6 Mpc^3 – the largest so far probed by a narrow-band survey at these wavelengths. The reader is referred to Sobral et al. (2009) – hereafter S09 – for details regarding the observations, data reduction and the general selection of narrow-band emitters. Here the focus will be on identifying Lyα emitters candidates within that data-set.

2.1   Search for Candidates

For a source to be considered a candidate $z \approx 9$ Lyα emitter it was required to: i) be selected as a narrow-band emitter in S09 (this required it to be clearly detected in NB$_J$ ($\sigma > 3$) and present a J-NB$_J$ colour excess significance with $\Sigma > 2.5$ and equivalent width EW> 50 Å – see S09 for details in which it is shown that these criteria are very robust); ii) have at least one other detection $> 3\sigma$ in the infrared; iii) be visually believable in NB$_J$ and the other band(s), avoiding noisy areas; and iv) be undetected (3σ and direct visual analysis) in the available visible band imaging (B,V,r,i,z) – SUBARU and ACS/HST).

The sample presented in S09 was used to search for potential Lyα emitters at $z \approx 9$. However, the investigation was also extended to a slightly larger area in the UKIDSS UDS field, to include areas where deep SUBARU and near-infrared imaging data were available – this corresponds to re-including areas which were conservatively masked for SED fitting purposes in S09, and pushes the total area to ~ 1.4 deg^2.

### 2.2   Candidates, testing and follow-up observations

No candidates were found in the UKIDSS UDS field, with all emitters that passed tests i) to iii) being clearly detected in z-band imaging. In COSMOS, however, 2 candidates were found that satisfied all criteria. Both sources are absent in all visible bands down to the 3σ level (e.g. I = 28.1 mag, z = 25.8 mag). They both present clear NB$_J$ and J detections, with Cand 1 having NB$_J$ = 20.8 mag (5σ) and J = 21.5 mag (9σ) and a drop $z - J > 4.2$ mag, while Cand2 presents NB$_J$ = 20.8 mag (5σ) and J = 22.1 mag (6σ) and a drop $z - J > 3.6$ mag. They are both undetected in all other infra-red bands.

These two sources were then subjected to a series of tests and follow-up observations. Splitting the data into subsets confirmed the detections across different nights, with no evidence for variability or proper motion. Cand1 was followed-up spectroscopically using the CGS4 instrument on UKIRT in January 2009 – these data failed to confirm an emission line. Both candidates were then re-observed using WFCAM on UKIRT (J imaging in February 2009), resulting in the non-detection of both candidates. Also, J imaging data from COSMOS (which have become publicly available very recently) fail to detect the candidates. It is therefore clear that these sources are not Lyα emitters at $z \sim 9$; further investigation shows that the sources are artifacts; they are located at almost exactly the same pixel position on WFCAM4 in 2 different paw-prints (later investigation showed that these were also found at similar pixel positions in the remaining 2 paw-prints, although at a lower level, and thus were not selected). They are caused by an unfortunate coincidence of a set of slightly hot pixels (not sufficient to be flagged as bad pixels) which, combined with the ditter pattern, produced a few sigma excess at one location on the combined image. No other artifacts like these were found either in UDS (which used a different dither pattern) or in other cameras for COSMOS data.

3   RESULTS & DISCUSSION

3.1   Lyα Luminosity function at $z \sim 9$

After conducting the widest survey of bright (L $> 7.6 \times 10^{43}$ erg s^{-1}) Lyα emitters at $z \sim 9$, probing a co-moving volume of 1.07×10^6 Mpc^3 (1.4 deg^2), only 2 sources passed the selection criteria and even those were ruled out after follow-up ob-
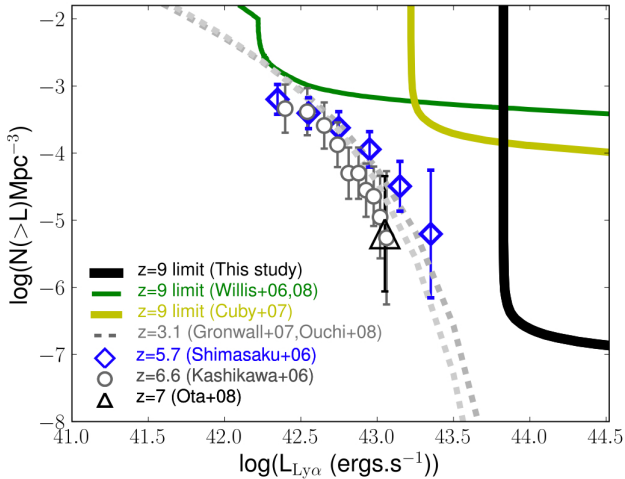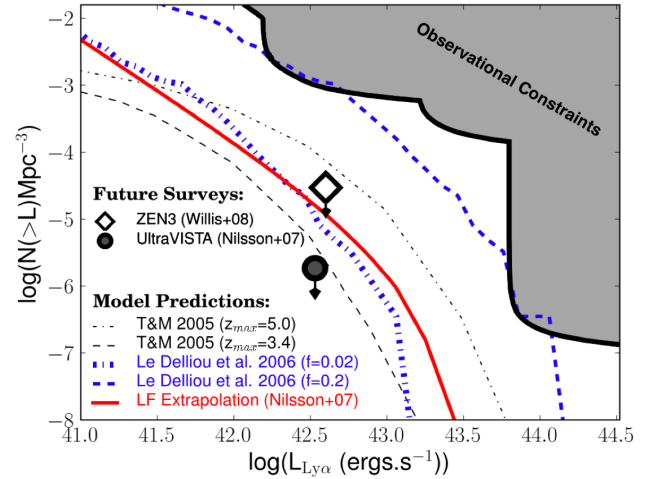
Figure 1. Comparison between the measured Lyα luminosity function at $z \sim 3$ (dotted lines; Gronwall et al. 2007; Ouchi et al. 2008) with data from $z \sim 6 - 7$ (Kashikawa et al. 2006; Shimasaku et al. 2006; Ota et al. 2008). Other typically smaller $z \sim 6$ surveys give consistent results within the error bars. No evidence of significant evolution is found, especially when accounting for cosmic variance. Limits for the $z \sim 9$ LF from Willis & Courbin (2005), Cuby et al. (2007) and Willis et al. (2008) are also presented, together with the one presented in this Letter, which is inconsistent with a strong evolution in L* up to $z \sim 9$.

Figure 2. The observational limits on the $z \sim 9$ Lyα luminosity function compared to different model predictions and proposed future surveys. The most recent models agree well with the data limits, and only the most extreme ones can be ruled out. Also, according to these models, the UltraVISTA survey will have a clear chance of detecting a few of these Lyα emitters, while ZEN3 may get a detection and will at least be able to rule out more models.

servations. This result allows the tightest constraint on the bright end of the $z \sim 9$ Lyα luminosity function, as previous surveys have only covered very small areas (a factor $\sim$1000 smaller). However, those surveys have gone significantly deeper (up to a factor of $\sim$100). Thus, by combining all the results from the literature, the luminosity function of LAEs at $z \sim 9$ can be constrained across a wide range of luminosities: $10^{42} < L < 10^{44}$ erg s^{-1}. Figure 1 presents such constraints from Willis & Courbin (2005), Cuby et al. (2007), Willis et al. (2008) and from this work, with the lines presenting the inverse of the volume selection function for each survey. These are compared to the measured Lyα luminosity functions from $z \sim 3$ to $z \sim 7$ from recent studies. Although the samples of Lyα emitters may suffer from significant biases due to selection/cosmic variance/contamination, Figure 1 reveals that there is little evolution in the bright end of the luminosity function between $z \sim 3$ and $z \sim 5.7$. However, those bright emitters seem to become much rarer at $z = 6.5$ (Kashikawa et al. 2006), indicating that L* is not rising from $z \sim 6$ onwards. The results presented in this Letter are also consistent with L* not rising significantly (Δlog(L*)<0.5) from $z = 5.7$ to $z \sim 9$.

3.2 Comparison with models and future surveys

Several authors have tried to predict the Lyα luminosity function at $z \sim 9$, either by extrapolating the luminosity function of these emitters from lower redshift, or by using numerical or semi-analytical models. In this Letter, different models are compared with the observational constraints: semi-analytical models, observational extrapolations and phenomenological models. The semi-analytical models discussed here are obtained with GALFORM (Baugh et al. 2005) – these are based on ΛCDM, having been successful in reproducing a wide range of galaxy properties at different redshifts, including Lyα emitters up to $z \sim 6$ (Le Delliou et al. 2006). GALFORM computes the build-up of dark matter halos by merging and the assembly of baryonic mass of galaxies and the

semi-analytical approach allows the study of properties of the Lyα emission – the reader is referred to both Baugh et al. (2005) and Le Delliou et al. (2006) for more details on these. The observational approach, as in Nilsson et al. (2007), extrapolates the Schechter function parameters based on those obtained in the $3.1 < z < 6.5$ redshift range. In practice, this results in little L* evolution but a significant negative ϕ^* evolution. Finally, the phenomenological approach in Thommes & Meisenheimer (2005) assumes that Lyα emitters at high redshift are spheroids seen during their formation phase. These models are normalised to give the observed mass function of spheroids in the local universe, and are combined with a phenomenological function that provides the distribution of spheroid formation events in mass and redshift. Each galaxy is assumed to be visible as a Lyα emitter during a starburst phase of fixed duration that occurs at a specific redshift, drawn from a broad distribution. The reader is referred to Thommes & Meisenheimer (2005) for details.

Figure 2 presents predictions from GALFORM (Le Delliou et al. 2006) for two Lyα escape fractions, the observational luminosity function extrapolation from Nilsson et al. (2007) and updated phenomenological predictions (Thommes & Meisenheimer 2005) assuming peak redshifts of $z_{max} = 3$ and $z_{max}5$. While most models are consistent with the current limits, GALFORM models with high escape fractions are marginally rejected both at faint and bright levels. Earlier phenomenological models (e.g. the $z_{max} = 10$ model of Thommes & Meisenheimer 2005, not shown in Figure 2) are also clearly rejected.

These results also show, observationally, that bright $L > 10^{43.8}$ erg s^{-1} Lyα emitters are very rare. Although the area coverage is absolutely important, a depth+area combination is likely to be the best approach for gathering the first sample of these very high-redshift galaxies. In fact, that is the strategy of the narrowband component of the UltraVISTA survey (c.f. Nilsson et al. 2007), using the VISTA telescope, which will map the COSMOS field (total area of 0.9 deg^2) to a planned flux limit of 4×10^{-18} erg s^{-1} cm^{-2} (5σ); this corresponds to luminosity limit of $L = 10^{42.53}$ erg s^{-1} and a surveyed volume of 5.41×10^5 Mpc^3 (see

Figure 2). This combination lies below all current predictions for the $z \sim 9$ Lyα LF and the survey is expected to detect 2-20 Lyα emitters at $z = 8.8 \pm 0.1$. On the other hand, the ZEN3 survey (c.f. Willis et al. 2008) will also try to get a compromise between area and depth by taking advantage of the Canada-France-Hawaii Telescope (CFHT) and their near-infrared large area camera (WIRCam); that survey will not go as wide or as deep, and whilst it will provide significantly better constraints, it is not clear (as can be seen in Figure 2) whether or not it will be successful in detecting any Lyα emitter.

3.3   High redshift Lyα searches and cool galactic stars

It has become widely realised in recent years that broad-band searches for $z > 6$ galaxies using the Lyman-break technique may suffer from significant contamination by cool galactic L, T, and possibly Y-dwarf stars (e.g. McLure et al. 2006). These low-mass brown dwarfs display extremely red $z - J$ colours reaching as high as $z - J \approx 4$ (e.g. Burningham et al. 2008), coupled with relatively flat $J - K$ colours. Such colours can mimic very closely those expected of a $z > 6$ star forming galaxy with a strong Lyman-break.

It may be thought that narrow-band Lyα searches are immune to this contamination, since the initial emission-line galaxy selection relies on an excess flux observed in a narrow-band filter relative (usually) to a broad-band filter; only after that is the Lyman-break technique used to pick out the high-redshift Lyα candidates from amongst the emission-line objects. However, the near-infrared continuum spectra of low mass brown dwarfs show considerable structure, due to broad molecular absorption features (especially methane and ammonia; e.g. Leggett et al. 2007), as shown in the top panel of Figure 3. The lower panel of Figure 3 shows very clearly that T-dwarfs can easily produce a positive broad-band minus narrow-band (BB-NB) colour if the narrow-band filter is located within one of the spectral peaks (note that this is much less of an issue for surveys which difference two closely-located narrow-band filters). Lyα narrow-band surveys in the redshift ranges $7.7 < z < 8.0$, $9.1 < z < 9.5$ and $11.7 < z < 12.2$ may therefore be prone to contamination by cool galactic stars – this includes the $z = 7.7$ and $z = 9.4$ atmospheric windows for narrow-band searches of Lyα emitters. Narrow-band surveys at redshifts $z < 7.5$, or between $8.0 < z < 9.1$ – which includes both HiZELS ($z = 8.96$) and the narrow-band component of the UltraVISTA Survey ($z = 8.8$; e.g. Nilsson et al 2007) – will be free of such contamination. Indeed, such surveys could potentially select very cool T-dwarf stars via a narrow-band *deficit* due to the strong methane absorption feature at these wavelengths.

With this result in mind, a T-dwarf search was conducted among narrow-band *deficit* sources in S09. These *deficit* sources were selected using equivalent criteria as for emitters (with a change in sign). None of the *deficit* sources presents z(AB)$-J >$ 3, as expected for T-dwarfs (e.g. Leggett et al. 2007, Burningham et al. 2008), and even a selection imposing z(AB)$-J > 2$ results in a sample of only 9 galaxies which are all very well SED-fitted as galaxies with $z_{photo} \sim 1.4 - 1.5$. These sources also present slightly higher J and H fluxes when compared to the best SED fit, but this can be explained by the Hβ and [OIII] contributing to the J band and Hα to the H band, which also explains the NB$_J$ deficit. No T-dwarf candidate was found for this survey.
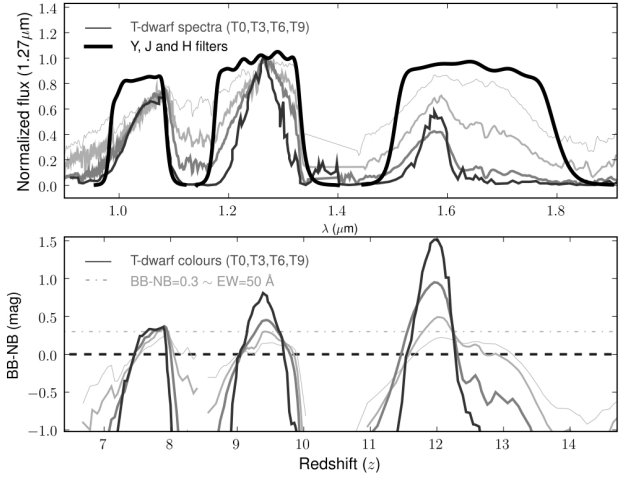
Figure 3. *Top panel:* the near-infrared spectra of T0, T3, T6 and T9 dwarf stars (T0 – lighter, T9 – darker, from Burningham et al. 2008)) compared to near-IR broad band filter profiles. *Lower panel:* the consequences for measured broad-band minus narrow-band (BB-NB) colours, clearly demonstrating the redshifts/wavelengths at which searches for Lyα emitters can be significantly contaminated by these very cool stars. For $7.7 < z < 8.0$ and $9.1 < z < 9.5$ searches, these stars can easily mimic Lyα emitters, with strong Y-z or J-z breaks and significant positive BB-NB colours. Searches at higher redshift $11.6 < z < 12.2$ in the H band can detect T9s with BB-NB$\sim$1.5, although the lack of strong H-J or H-Y breaks will make it easier to distinguish T-dwarfs from Lyα emitters.

4   SUMMARY

- Deep narrow-band imaging in the J band has been used to search for bright Lyα emitters at $z = 8.9$ over an area of 1.4 deg^2. No Lyα emitter was found brighter than L $> 7.6 \times 10^{43}$ erg s^{-1}.
- The Lyα luminosity function constraints at $z \sim 9$ have been improved for $10^{42} < L < 10^{44}$ erg s^{-1} emitters. The results are consistent with negative evolution of the Lyα LF beyond $z \sim 6$ and are in line with recent semi-analytic & phenomenological model predictions, rejecting some extreme models.
- It has been shown that for narrow-band searches, T-dwarfs can mimic Lyα emitters at $7.7 < z < 8.0$, $9.1 < z < 9.5$ and $11.7 < z < 12.2$; they will not contaminate the future UltraVISTA narrow-band survey (and can even be identified via a narrow-band *deficit*), but they may contaminate narrow-band Lyα searches within the $z = 7.7$ and $z = 9.4$ atmospheric windows.

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