

## LETTERS

# Escape of about five per cent of Lyman- $\alpha$ photons from high-redshift star-forming galaxies

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The Lyman- $\alpha$  ( $\text{Ly}\alpha$ ) emission line is the primary observational signature of star-forming galaxies at the highest redshifts<sup>1</sup>, and has enabled the compilation of large samples of galaxies with which to study cosmic evolution<sup>2–5</sup>. The resonant nature of the line, however, means that  $\text{Ly}\alpha$  photons scatter in the neutral interstellar medium of their host galaxies, and their sensitivity to absorption by interstellar dust may therefore be greatly enhanced. This implies that the  $\text{Ly}\alpha$  luminosity may be significantly reduced, or even completely suppressed. Hitherto, no unbiased empirical test of the escaping fraction ( $f_{\text{esc}}$ ) of  $\text{Ly}\alpha$  photons has been performed at high redshifts. Here we report that the average  $f_{\text{esc}}$  from star-forming galaxies at redshift  $z = 2.2$  is just 5 per cent by performing a blind narrowband survey in  $\text{Ly}\alpha$  and  $\text{H}\alpha$ . This implies that numerous conclusions based on  $\text{Ly}\alpha$ -selected samples will require upwards revision by an order of magnitude and we provide a benchmark for this revision. We demonstrate that almost 90 per cent of star-forming galaxies emit insufficient  $\text{Ly}\alpha$  to be detected by standard selection criteria<sup>2–5</sup>. Both samples show an anti-correlation of  $f_{\text{esc}}$  with dust content, and we show that  $\text{Ly}\alpha$ - and  $\text{H}\alpha$ -selection recovers populations that differ substantially in dust content and  $f_{\text{esc}}$ .

The hydrogen  $\text{Ly}\alpha$  emission line, thanks to its high intrinsic luminosity ( $L_{\text{Ly}\alpha}$ )<sup>1</sup>, high equivalent width ( $W_{\text{Ly}\alpha}$ )<sup>6,7</sup> and very convenient rest-frame wavelength (1,216 Å), continues to act as a staple tracer of distant star-forming galaxies. However, the  $\text{Ly}\alpha$  transition is a resonant one, causing photons to scatter in the neutral hydrogen component (H I) of the interstellar medium, so that path lengths to escape may be greatly increased compared to non-resonant radiation. Thus, depending on the content, distribution and kinematics of H I, and the dust content,  $f_{\text{esc}}$  for a galaxy may fall anywhere within the range of 0 to 1 (refs 8–11). It follows that for the field of  $\text{Ly}\alpha$  astrophysics to bloom—from using the line to select high- $z$  galaxies, to a physically meaningful diagnostic of star formation—a detailed empirical examination of  $f_{\text{esc}}$  in cosmological galaxies is essential.

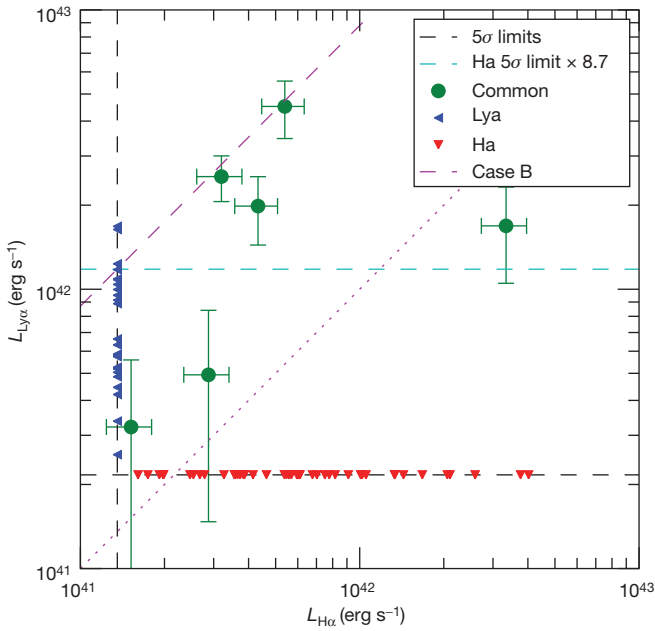
Estimating  $f_{\text{esc}}$  at high  $z$  is extremely challenging, because the requisite supporting data are observationally expensive to obtain. Comparison of star-formation rates (SFR) derived from  $\text{Ly}\alpha$  with those from ultraviolet continuum can be used to infer  $\langle f_{\text{esc}} \rangle = 30\text{--}60\%$  from several studies of  $z = 2$  and 3  $\text{Ly}\alpha$  samples<sup>4,5,12</sup>. However, this assumes that the ultraviolet continuum is un-attenuated, and is strongly dependent on models of stellar evolution to provide the respective SFR calibrations<sup>13</sup>. Furthermore, this technique is only valid if star formation has proceeded at a constant rate over the last  $\sim 100$  Myr. More importantly, restricting analysis to  $\text{Ly}\alpha$ -selected samples neglects potential star-forming galaxies that do

not show  $\text{Ly}\alpha$  emission. Comparing independently determined  $\text{Ly}\alpha$  and ultraviolet luminosity functions provides an alternative, but cosmic variance can easily introduce errors of a factor of two (ref. 5), and the aforementioned uncertainties in SFR calibration remain. Using theoretical galaxy formation models, lower values of  $f_{\text{esc}} = 2\%$  (ref. 14) to 10% (ref. 15) have been estimated at  $z = 3$ , but these methods suffer from the large number of *ad hoc* parameter assumptions that enter the models. A significant step forward can be taken if  $\text{Ly}\alpha$  is compared with another, non-resonant hydrogen recombination line (for example,  $\text{H}\alpha$ ), since both intrinsic strengths are a direct function of the ionizing luminosity. This has been done at  $z = 0.3$ , placing  $f_{\text{esc}} = 1\text{--}2\%$  (ref. 16) but cosmological application is restricted by the  $>7$  billion years over which galaxies can evolve to  $z > 2$ .

With a new, very deep survey using the ESO Very Large Telescope (VLT), we have overcome all of these issues simultaneously. We have performed a blind, unbiased, narrowband imaging survey for  $\text{H}\alpha$  and  $\text{Ly}\alpha$  emission at  $z = 2.2$  using custom manufactured filters to guarantee the same cosmic volume is probed in both emission lines (Supplementary Information). Thus, although cosmic variance does affect the number of objects in our survey volume, its effect cancels from any volumetric properties we derive by comparison of the two samples. With observational limits sensitive to un-obscured SFRs of 1.9 solar masses per year ( $1.9M_{\odot} \text{ yr}^{-1}$ ) in  $\text{H}\alpha$ , we identify 55 new  $\text{H}\alpha$  emitters<sup>17</sup>.  $\text{Ly}\alpha$  observations are sensitive to  $\text{SFR} = 0.26M_{\odot} \text{ yr}^{-1}$  assuming  $f_{\text{esc}} = 1$  ( $f_{\text{esc}} = 0.13$  for the faintest  $\text{H}\alpha$  emitters), and we identify 38 new galaxies.  $\text{Ly}\alpha$  and  $\text{H}\alpha$  luminosities are shown in Fig. 1 (see also Supplementary Information). Targeting the GOODS-South<sup>18</sup> field, we benefit from some of the deepest broadband optical and infrared data in existence, compiled into public source catalogues<sup>19</sup>. From these we obtain stellar spectral energy distributions (SEDs), which allow us to estimate dust content ( $E_{B-v}$ ) and intrinsic SFR. We find all the  $\text{H}\alpha$  galaxies and 21 of the  $\text{Ly}\alpha$  emitters in public catalogues.

From the  $\text{Ly}\alpha$  sample we construct the observed  $\text{Ly}\alpha$  luminosity function,  $\text{LF}(\text{Ly}\alpha)$ . Using the same formalism, we derive the first intrinsic  $\text{Ly}\alpha$  luminosity function,  $\text{LF}(\text{Ly}\alpha)$ , from the  $\text{H}\alpha$  sample, using measurements of  $E_{B-v}$  to correct the  $\text{H}\alpha$  luminosity for extinction, and assuming the standard  $\text{Ly}\alpha/\text{H}\alpha$  line ratio of 8.7 for ionization bounded nebulae<sup>20</sup> ('case B'; see Fig. 2). In this way, we obtain the intrinsic and observed  $\text{Ly}\alpha$  luminosity densities, the ratio of which leads us directly to a volumetric  $f_{\text{esc}} = (5.3 \pm 3.8)\%$ , with no dependence on cosmic variance, the evolutionary state of the galaxies, or calibration uncertainties. The method is sensitive to the dust correction, as we assume that the same extinction applies to the

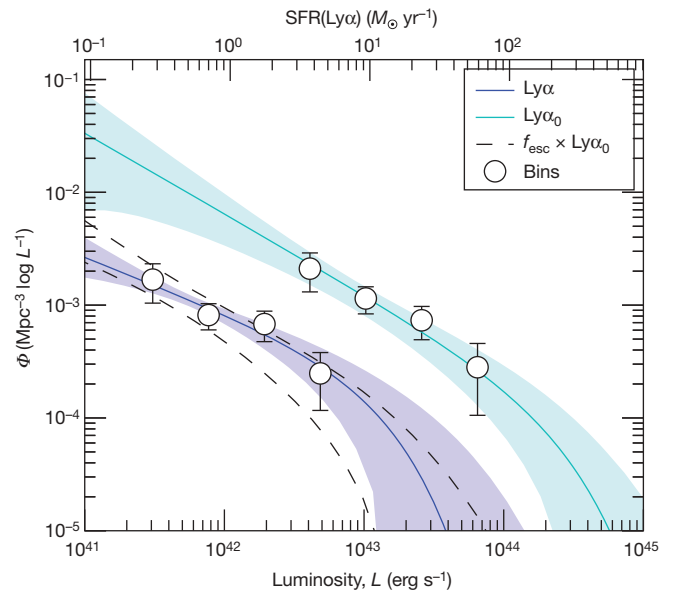
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**Figure 1 | Observed H $\alpha$  and Ly $\alpha$  luminosities.** Sources detected only in H $\alpha$  are shown in red, those detected only in Ly $\alpha$  in blue, and common detections in green. All error bars are  $1\sigma$  photometric uncertainties. Objects undetected in Ly $\alpha$  or H $\alpha$  are represented as upper limits placed at the detection limits of the H $\alpha$  or Ly $\alpha$  data, respectively (black dashed lines). The dashed magenta line shows the Ly $\alpha$ /H $\alpha$  ratio for case B recombination in the absence of dust, and the dotted line shows Ly $\alpha$  = H $\alpha$ . For a sample of dust-free galaxies, complete in both lines, all objects should line up on the recombination line, with dust and the effects of radiation transfer serving only to move objects away from the line in the direction of  $L_{\text{Ly}\alpha} < 8.7L_{\text{H}\alpha}$ . The dashed cyan line shows 8.7 times the  $5\sigma$  detection limit for H $\alpha$  applied to the  $L_{\text{Ly}\alpha}$  axis. For the case B recombination ratio, all galaxies falling above this line should be detected in H $\alpha$  (see Supplementary Information for more details). No objects occupy this region of the diagram with significance above  $1\sigma$ .

continuum and to H $\alpha$ , and thus we perform the same test without correcting H $\alpha$  luminosities for dust, finding the most conservative upper limit of  $(10.7 \pm 2.8)\%$  — a limit free of any model dependency whatsoever. This first key result shows that commonly practised survey estimates of the total Ly $\alpha$  luminosity density at  $z \geq 2$  will significantly underestimate its intrinsic value: on average, only 1 in 20 of the intrinsic Ly $\alpha$  photons reaches the telescope. This may not be surprising at the highest redshifts (that is, above  $z = 6$ ) where an increase in the neutral fraction of the intergalactic medium may cause significant suppression of the Ly $\alpha$  line<sup>21–23</sup>, but at  $z = 2–4$  this effect is likely to be small, and the photons must be lost in the interstellar medium of individual galaxies. This result is especially consequential, because the integrated luminosity density converts directly to the cosmic rate of star-formation, implying that pure Ly $\alpha$ -based estimates of volumetric SFR are in need of strong upward revision.

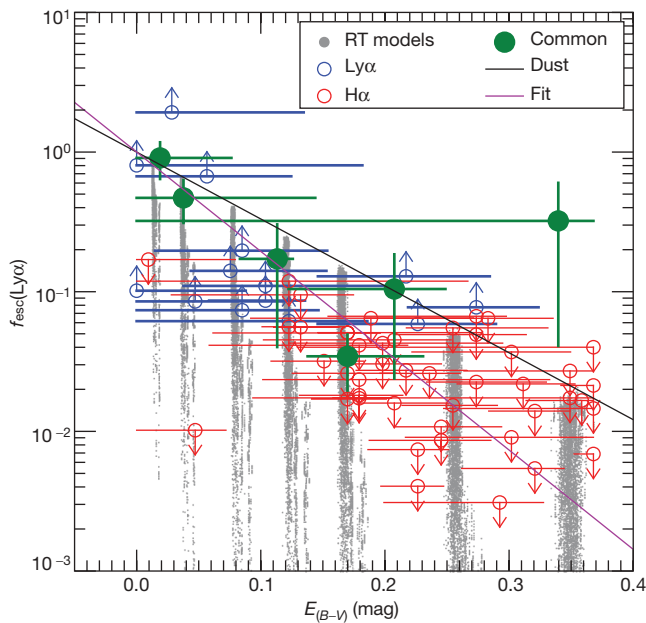
To investigate the origin of this underestimate, we examine the individual galaxies. Having modelled the SEDs<sup>24</sup> for all the objects found in the broadband catalogues, we obtain homogeneous derivations of dust extinction ( $E_{B-V}$ ) and SFR for both samples. From the Ly $\alpha$  and H $\alpha$  luminosities,  $E_{B-V}$  estimates and recombination theory, we compute  $f_{\text{esc}}$  in individual sources (limits on  $f_{\text{esc}}$  are derived for sources detected in only one line by assigning the  $1\sigma$  limiting flux to non-detections). In Fig. 3 we show how  $f_{\text{esc}}$  correlates with  $E_{B-V}$  for our observed galaxies, where we also plot the position of 50,000 synthetic galaxies generated using the ‘MCLya’ radiation transfer code<sup>25</sup>, and the  $f_{\text{esc}}-E_{B-V}$  relationship expected from pure dust attenuation<sup>26</sup>. All the synthetic galaxies fall below the theoretical curve, and every observed galaxy except for one lies within  $1\sigma$  of this region. This demonstrates how Ly $\alpha$  photons are preferentially absorbed in the interstellar medium of almost all of our galaxies.



**Figure 2 | Ly $\alpha$  luminosity functions.**  $\Phi$  is the number density of galaxies per decade in luminosity; the SFR labelled on the upper abscissa corresponds directly to the luminosity on the lower. The luminosity function shaded blue, at lower luminosity, shows the observed luminosity distribution, derived from the VLT/FORS1 observations. The function shaded cyan, at higher luminosity, shows the intrinsic luminosity function, denoted  $\text{LF}(\text{Ly}\alpha_0)$ , derived from the HAWKI observations by correcting the H $\alpha$  luminosities for dust attenuation, and multiplying by the case B Ly $\alpha$ /H $\alpha$  ratio of 8.7. Black open circles show the bins of the respective luminosity functions, with vertical error bars representing 68% confidence limits. For the observed  $\text{LF}(\text{Ly}\alpha)$ , this error is derived from Poisson statistics and incompleteness simulations alone. For the intrinsic  $\text{LF}(\text{Ly}\alpha)$ , the error bar also includes the error on the dust correction which is randomized on every realization of the Monte Carlo simulation, allowing galaxies to jump between adjacent bins (see Supplementary Information for details). The shaded regions associated with each luminosity function represent the regions of 68% confidence derived from the Monte Carlo. For each realization, both intrinsic and observed  $\text{LF}(\text{Ly}\alpha)$  are regenerated and fitted with the Schechter function; integration over luminosity between 0 and infinity then provides us with the observed and intrinsic Ly $\alpha$  luminosity densities. Volumetric  $f_{\text{esc}}$  follows directly as the ratio of these two quantities, and is found to be  $(5.3 \pm 3.8)\%$ . Scaling the 68% limits of the intrinsic  $\text{LF}(\text{Ly}\alpha)$  by this fraction in luminosity results in the dashed black lines, which clearly and comfortably encompass the observed distribution.

Despite the nonlinearity introduced by the multi-parametric Ly $\alpha$  transfer problem,  $f_{\text{esc}}$  and  $E_{B-V}$  remain clearly anti-correlated. The correlation shows a gradient that is 50% steeper than that predicted by pure dust attenuation: the effective extinction coefficient,  $k_{1216}$ , is found to be 17.8 instead of 12 for normal attenuation<sup>26</sup>. More striking in Fig. 3 is the lack of overlap and significant offset between the populations: the Ly $\alpha$  and H $\alpha$  samples are almost disjoint in both quantities. We measure median values of  $E_{B-V} = 0.085$  (0.23) and  $f_{\text{esc}} > 0.32$  ( $< 0.035$ ) for Ly $\alpha$  (H $\alpha$ ) emitters. Furthermore, we find the median SFRs to be very different between the two samples:  $3.5M_{\odot} \text{ yr}^{-1}$  for Ly $\alpha$ , and  $10.0M_{\odot} \text{ yr}^{-1}$  for H $\alpha$ . Thus Ly $\alpha$  galaxies are significantly less powerful in forming stars, less dusty, and show higher  $f_{\text{esc}}$  than H $\alpha$  galaxies. For Ly $\alpha$ , these estimates are based on the 21 brighter galaxies found in public source catalogues and including the remainder would be likely to increase the disparity between the samples. In  $f_{\text{esc}}$  the difference is further accentuated by the fact that we are considering lower and upper limits for the Ly $\alpha$  and H $\alpha$  samples, respectively.

Another significant result is that of 55 H $\alpha$  and 38 Ly $\alpha$  emitters, we detect only 6 galaxies in both lines. These galaxies straddle the individual distributions, with 5 of the 6 falling within  $1\sigma$  of the dust attenuation curve. This is unsurprising when examined in light of



**Figure 3 | Escape fraction ( $f_{\text{esc}}$ ) and dust attenuation ( $E_{B-V}$ ).** All objects found in the broadband photometry catalogue (that is, for which we can recover  $E_{B-V}$ ) are included. Green shows galaxies detected in both lines, blue shows detections only in Ly $\alpha$ , and red shows detections only in H $\alpha$ . All error bars are derived from propagation of measurement and model fit uncertainties, and represent 68% confidence. The grey clouds show the positions of 50,000 synthetic galaxies produced using the MCLy $\alpha$  radiation transfer code, and are labelled RT models. The black line shows the dust attenuation law of Calzetti, which should be valid in the absence of resonance scattering. The magenta line shows the relation that best fits the observed data points using Schmitt's binned linear regression algorithm<sup>30</sup>, a survival analysis algorithm able to account for data points and limits in both directions which does not require a priori knowledge of the distribution of the censored parent population. The number of data points is 67 (55 H $\alpha$  emitters + 18 Ly $\alpha$  emitters – 6 common detections). Parameterized as  $f_{\text{esc}} = 10^{-0.4 \times E_{B-V} \times k_{1216}}$ , we find the extinction coefficient  $k_{1216}$  to be 50% higher ( $k_{1216} = 17.8$  instead of 12.0) than the curve of pure dust attenuation. All but a few data points fall in the region swept out by the radiation transfer code, and demonstrate the significance of the spatial and kinematic structure of the neutral interstellar medium in the transfer of photons. Furthermore it is clear that the areas of the  $f_{\text{esc}}-E_{B-V}$  diagram populated by Ly $\alpha$ - and H $\alpha$ -selected galaxies are almost disjoint: the Ly $\alpha$  sample are significantly less dusty and exhibit higher escape fractions than the H $\alpha$  sample. This clearly shows how the populations recovered by the respective selection functions are very different, despite the fact that the physics governing the production of the two emission lines is identical.

the individual samples, but it is unlikely that such a relationship would have been predicted on the basis of the  $z \approx 0$  objects of similar luminosity, where little obvious correlation is found between the two line intensities<sup>8,27–29</sup>. The fact that so few H $\alpha$  emitters are detected in Ly $\alpha$  can be attributed to a combination of two factors. First, the extinction coefficient at Ly $\alpha$  is substantially larger than at H $\alpha$  ( $k_{1216} = 12.0$  compared to  $k_{6563} = 3.33$ )<sup>26</sup>: the median  $E_{B-V}$  for the H $\alpha$  emitters corresponds to a 50% reduction in H $\alpha$  luminosity but an  $f_{\text{esc}}$  value of just 7%. Second, the fact that only Ly $\alpha$  scatters serves to exacerbate this, and the grey points in Fig. 3 show how  $f_{\text{esc}}$  can be reduced to below 1%, even with minuscule dust contents. Indeed, for constant star formation (after the equilibrium time of  $\sim 100$  Myr) with a 'standard' initial mass function and metallicity,  $W_{\text{Ly}\alpha}$  is  $\sim 80 \text{ \AA}$  (refs 6, 7), and preferential suppression of Ly $\alpha$  by just a factor of 4 would render a galaxy undetected in the survey. Short-lived burst scenarios increase  $W_{\text{Ly}\alpha}$  to  $>200 \text{ \AA}$  (refs 6, 7), requiring preferential attenuation factors of  $\sim 10$ ; these are still easily attainable at very modest  $E_{B-V}$  (ref. 11). Similarly, the low number of Ly $\alpha$  sources detected in H $\alpha$  is explained by the large range of escape fractions exhibited by star-forming galaxies: Ly $\alpha$  selection preferentially

finds galaxies with higher  $f_{\text{esc}}$  values and smaller attenuation in H $\alpha$ , resulting in line ratios nearer the recombination value and comparatively faint H $\alpha$ . This pushes the H $\alpha$  fluxes below our detection limit for most galaxies, despite the very deep H $\alpha$  data.

Increasing the number of co-incident detections is extremely challenging observationally. Owing to the wide range of relative line intensities, a large range of luminosities needs to be spanned in both lines, requiring each observation to be both wide and deep. This is currently feasible in Ly $\alpha$ , but large ( $\sim 0.5 \text{ degree}^2$ ) infrared imagers are still non-existent on telescopes of the 8–10-m class. Extending this survey to higher redshift will remain unfeasible until the James Webb Space Telescope comes online.

Received 28 September 2009; accepted 29 January 2010.

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**Supplementary Information** is linked to the online version of the paper at [www.nature.com/nature](http://www.nature.com/nature).

**Acknowledgements** This work is based on observations made with ESO telescopes at the Paranal Observatory under programme ID 081.A-0932. The filter used to capture Ly $\alpha$  was financed by the Erik and Märta Holmberg foundation for astronomy and physics. M.H., D.S. and S.d.B. acknowledge the support of the Swiss National Science Foundation. G.Ö. is a Swedish Royal Academy of Sciences research fellow supported by the Knut and Alice Wallenberg foundation, and also acknowledges support from the Swedish research council (VR). J.M.M.-H. is

funded by Spanish MICINN grants CSD2006-00070 (CONSOLIDER GTC) and AYA2007-67965. We thank D. Valls-Gabaud, M. Ouchi, and C. Scarlata for discussions.

**Author Contributions** M.H. and G.Ö. conceived the programme and manufactured the custom filter. M.H. observed, and processed and analysed the data. S.d.B. and D.S. wrote tools for analysis of the SED fitting results. A.V. produced the radiation transfer code with D.S. J.M. contributed to the use and processing of auxiliary data. All authors contributed to the interpretation of the data, the research proposal and manuscript preparation.

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