

# Near-Infrared Integral Field Spectroscopy of Damped Lyman- $\alpha$ Systems

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**Abstract.** We assess the feasibility of detecting star formation in damped Lyman- $\alpha$  systems (DLAs) at  $z > 1$  through near-infrared spectroscopy using the forthcoming integral field units on 8 m-class telescopes. Although their relation to galaxies is not well established, high- $z$  DLAs contain most of the neutral gas in the Universe, and this reservoir is depleted with time – presumably through star formation. Line emission should be an indicator of star formation activity, but searches based on Lyman- $\alpha$  are unreliable because of the selective extinction of this resonant UV line. Using more robust lines such as H $\alpha$  forces a move to the near-infrared at  $z > 1$ . For line emission searches, spectroscopy is more sensitive than imaging, but previous long-slit spectroscopic searches have been hampered by the likelihood that any star forming region in the DLA galaxy disk would fall outside the narrow slit. The new integral field units such as CIRPASS on Gemini will cover sufficient solid angles to intercept these, even in the extreme case of large galactic disks at high redshift. On an 8 m-class telescope, star formation rates of  $< 1 M_{\odot} \text{ yr}^{-1}$  will be reached at  $z \approx 1.4$  with H $\alpha$  in the  $H$ -band. Such star formation rates are well below  $L^*$  for the high- $z$  Lyman-break population, and are comparable locally to the luminous giant H II complexes in M 101. It appears that instruments such as CIRPASS on Gemini will have both the sensitivity and the survey area to measure star formation rates in  $z > 1$  DLAs. These observations will probe the nature of damped Lyman- $\alpha$  systems and address their relation to galaxies.

## 1 Damped Systems and Galaxy Evolution

Traditionally, flux-limited selection has been used to chart galaxy evolution. The measurement of quasar absorption lines allows an independent approach to studying the history of galaxies. The highest hydrogen column density absorbers seen in the spectra of background QSOs – the damped Lyman- $\alpha$  systems (DLAs) – contain most of the neutral gas in the Universe at  $z > 1$  (ref. 1), although their exact relation to galaxies is not well established. The global history of star formation can be inferred from the evolution in the co-moving density of neutral gas (predominantly in DLAs) as it is consumed in star formation (Fig. 1a & refs. 2,3). The average star formation rate in each DLA depends then on their space density. One school of thought has  $z > 2$  DLAs being thick gaseous disks, the progenitors of massive spirals

(e.g., ref. 4). Alternatively, DLAs could be more numerous gas-rich dwarfs, potentially sub-galactic building blocks (e.g., Fig. 1b and refs. 5, 6 & 7).

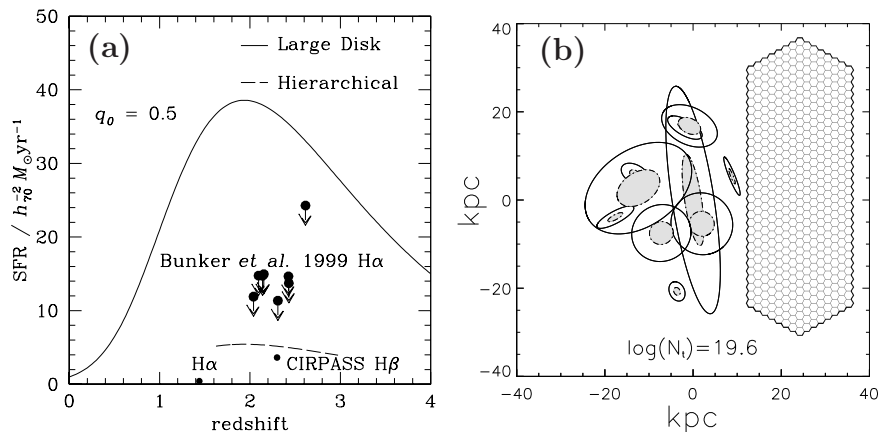
Hence, to determine the nature of the DLAs requires a measurement of their star formation rate. This is most directly done through the hydrogen recombination lines (e.g., ref. 8), which should have luminosity proportional to the photo-ionizing flux produced by the most massive and shortest lived OB stars (and therefore trace the near-instantaneous star formation rate). However, the largely unsuccessful searches for Ly $\alpha$  121.6 nm emission do not provide useful limits as this line is resonantly scattered and hence is selectively suppressed by dust absorption, which is difficult or impossible to quantify. Moving to the Balmer lines H $\alpha$  656.3 nm and H $\beta$  486.1 nm greatly reduces the problem of dust extinction, enabling the true star formation rates to be more accurately measured (e.g., ref. 9). For interesting redshifts where large samples of DLAs exist ( $z > 1$ ), these lines are redshifted into the near-infrared pass-bands.

## 2 Exploring DLAs with Near-IR Spectroscopy

Typically, we do not know where the star forming regions in the galaxy associated with the DLA actually are – all we know is that the sight-line to the background QSO passes through a large column of neutral hydrogen. The difficulties of point spread function subtraction of the QSO mean that broad-band imaging is unlikely to reveal the foreground galaxy in emission at small impact parameters (separations from the QSO sight line). However, spectroscopy is more effective for line emission searches because it is more sensitive and any emission line from the foreground DLA should be readily apparent against the continuum of the background QSO.

Recent near-infrared *K*-band long slit spectroscopy (ref. 10) with CGS 4 on the UKIRT 3.8m telescope failed to detect H $\alpha$  from star formation in 8 DLAs at  $z \approx 2.3$ . However, the long-slit approach may be ineffective, because of the high probability of any star forming region in the DLA galaxy falling outside the narrow slit. If DLAs really are  $\sim L^*$  galaxies, then they could extend over tens of kpc (several arcsec). Clearly, a larger solid angle needs to be surveyed. This will be achieved with the new generation of integral field units such as the Cambridge Infrared Panoramic Survey Spectrograph (CIRPASS, ref. 11), which can cover  $13'' \times 4''$  with its 499 fibres.

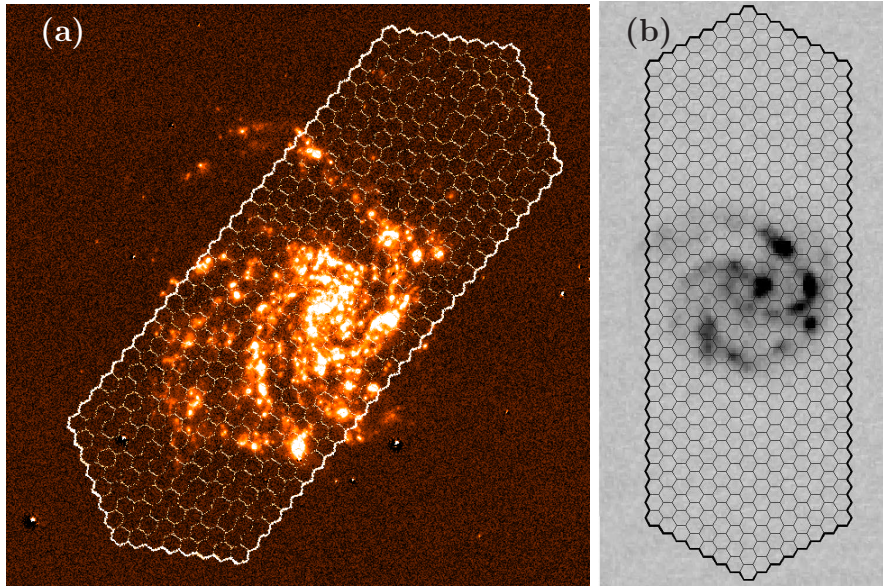
Although the gaseous disks may be large, the star-forming H II regions are likely to be compact (as in local spirals – e.g., Fig. 2a). The small size of star forming regions is consistent with observations of high-redshift galaxies in the rest-UV (Fig. 2b & ref. 12), and will be well-matched to the 0.25 arcsec CIRPASS fibres ( $\sim 1$  kpc across). A 3-hour integration on one of the 8 m Gemini telescopes should achieve a  $10\sigma$  sensitivity between the sky lines of  $10^{-20}$  W m $^{-2}$  at 1.6  $\mu$ m (*H*-band) for a compact source, conservatively assuming that 70% of the line emission from an H II region



**Fig. 1.** (a) The observational limits on the star formation rates in high-redshifted damped Lyman- $\alpha$  systems, based on H $\alpha$  near-infrared long-slit spectroscopy with CGS 4 on UKIRT (ref. 10). The solid curve is the predicted average star formation rates for a closed-box model (ref. 3) for the hypothesis where spirals today evolve from high-redshift large disks. The dashed curve is the prediction if present day spirals are assembled from hierarchical mergers of smaller, but more numerous, high-redshift DLAs (the hierarchical hypothesis). The curves plotted take no account of the possibility that the regions of star formation fall off the slit (which may be  $> 90\%$  of the cases using a spectroscopic slit). Also shown are the predicted sensitivities of the CIRPASS instrument on Gemini, which will test *all* these models, unlike the existing observations. The large area covered by the CIRPASS integral field unit means a much greater likelihood of intercepting any star forming regions. (b) A semi-analytic model of a halo with  $V_{\text{circ}} = 160 \text{ km s}^{-1}$  at  $z = 3$  (ref. 6). The shaded region shows the area of the disk with column density in excess of  $2 \times 10^{24} \text{ m}^{-2}$  (corresponding to DLAs). The overlaid CIRPASS fibres (0.25 arcsec across) shows that a single pointing of the integral field unit centred on a DLA will intercept most of the high column density gas – the potential sites of star formation

will fall within 4 fibres with seeing effects. For a cosmology with  $\Lambda = 0$ ,  $H_0 = 70 h_{70} \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $q_0 = 0.5(0.0)$ , then the star formation rates reached are  $0.6 (1.1) h_{70}^{-2} M_{\odot} \text{ yr}^{-1}$  for H $\alpha$  at  $z = 1.4$  and  $5.1 (14) h_{70}^{-2} M_{\odot} \text{ yr}^{-1}$  for H $\beta$  at  $z = 2.3$  (see ref. 8). Such star formation rates are well below  $L^*$  for the high- $z$  Lyman-break population (e.g. refs. 9 & 13) and are comparable locally to the luminous giant H II complexes in M 101.

It appears that instruments such as CIRPASS on Gemini will have both the sensitivity and the survey area to measure star formation rates in  $z > 1$  DLAs. Coupled with studies of the evolution of neutral hydrogen (ref. 2) and metal enrichment (ref. 14), these observations will probe the nature of damped Lyman- $\alpha$  systems and address their relation to galaxies.



**Fig. 2.** (a) An  $H\alpha$  image of the local spiral NGC 4254 as it would appear at  $z = 1.44$  with the CIRPASS integral field unit overlaid (using 0.25 arcsec diameter fibres). CIRPASS observations will test whether  $z > 1$  DLAs really are large disk galaxies. (b) A spiral galaxy at  $z \approx 1$  from the Hubble Deep Field  $B$ -band. The star-forming H II regions are prominent in the rest-frame UV. CIRPASS will accurately determine the true star formation rates, since (1) the compact knots of star formation are well-matched to the fibre size, reducing the sky background and increasing the sensitivity; (2) the large area surveyed by the integral field unit covers most of a spiral disk and (3) the  $H\alpha$  line is a much more robust measure of the star formation rate than the dust-suppressed UV continuum and resonantly-scattered Lyman- $\alpha$

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