Multi-object near-infrared Hα spectroscopy of z ∼ 1 star-forming galaxies in the Hubble Deep Field North

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ABSTRACT
We present preliminary results from a programme to obtain multi-object near-infrared spectroscopy of galaxies at redshifts 0.7 < z < 1.5. We are using the instrument CIRPASS (the Cambridge Infra-Red PAnoramic Survey Spectrograph), in multi-object mode, to survey Hα in galaxies at z ∼ 1. We aim to address the true star formation history of the Universe at this epoch: potentially the peak period of star formation activity. Hα is the same star formation measure used at low redshift, and hence we can trace star formation without the systematic uncertainties of using different calibrators in different redshift bins, or the extreme dust extinction in the rest-ultraviolet (rest-UV). CIRPASS has been successfully demonstrated in multi-object mode on the Anglo-Australian Telescope (AAT) and the William Herschel Telescope (WHT). Here we present preliminary results from one of our fields, the Hubble Deep Field North, observed with the WHT. With 150 fibres deployed over an unvignetted field of ∼15 arcmin, we have several detections of Hα from star-forming galaxies at 0.8 < z < 1.0 and present spectra of the seven brightest of these. By pre-selecting galaxies with redshifts such that Hα will appear between the OH sky lines, we can detect star formation rates of 5 \( h_{70}^{-2} \) M⊙ yr\(^{-1}\) (5σ in 3 hours, \( \Omega_M = 0.3, \Omega_\Lambda = 0.7 \)). It appears that star formation rates inferred from Hα are, on average, a factor of more than two higher than those based on the UV continuum alone.

Key words: instrumentation: spectrographs – galaxies: evolution – galaxies: formation – galaxies: high-redshift.

1 INTRODUCTION

A central problem in observational cosmology is determining at which epoch the majority of stars formed. This has important implications for models of galaxy formation and evolution. Despite recent progress in this area, the star formation history of the Universe is still a topic of intense debate. There is substantial evidence that the star formation rate was much higher in the recent past, compared with the current epoch, rising steeply to z ∼ 1 (e.g. Lilly et al. 1996; Tresse et al. 2002; Hippelein et al. 2003). However, it is still unclear whether at higher redshifts the star formation density declines, plateaus or perhaps continues to slowly increase. Most quantitative attempts to measure the global star formation history have suffered from having to use different indicators of star formation in various redshift bins (Madau et al. 1996), redshifted into the optical. These various indicators not only have uncertain relative calibration but are also affected differently by dust extinction. To make a reliable comparison, the same tracer of star formation must be used at high redshift as that used locally. The Hα emission line is a good tracer of the instantaneous star formation rate, and has been widely used in surveys at low redshift. It is particularly suitable as it is relatively immune to metallicity effects and is much less susceptible to extinction by dust than the rest-ultraviolet (rest-UV) continuum and Lyman α (which is also selectively quenched through resonant scattering). It is also important to use Hα to calibrate secondary indicators of star formation such as [O II] 3727 Å, which are often used at redshift one. However, tracing Hα to early epochs forces a move to the near-infrared (near-IR) at z > 0.6. The recent advent of good IR spectrographs on large telescopes has facilitated rapid advancement in this area, with observations of a few tens of galaxies at z ∼ 1 (e.g. Tresse et al. 2002; Glazebrook et al. 1999) and z ∼ 2...

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(Erb et al. 2003). However, until recently, near-IR spectroscopy has been restricted to long-slit work, and building samples using single object spectroscopy is inefficient in terms of telescope time. The small statistical samples obtained result in large uncertainties in the global properties of galaxies at $z \sim 1$. There has been successful ‘multi-object’ spectroscopy through slitless surveys in the near-IR from space (the Hubble Space Telescope/NICMOS survey of Yan et al. 1999), but such an approach has poor sensitivity because of the high background. It is only now that true multi-object infrared spectroscopy is possible from the ground, using either a slitmask approach (e.g. IRIS 2 and FLAMINGOS) or a fibre-fed spectrograph. In this paper we present the first successful demonstration of multi-object near-IR spectroscopy of high-redshift galaxies.

We have used our fibre-fed CIRPASS spectrograph (Cambridge InfraRed Panoramic Survey Spectrograph, Parry et al. 2000) to measure the star formation rates of a sample of galaxies in Hubble Deep Field North (HDF-N) (Williams et al. 1996). This is the initial stage of a larger survey to address the true star formation history of the Universe at redshifts $z = 0.7–1.5$, through Hz measurements of several hundred galaxies. CIRPASS can operate with a 150-fibre multi-object bundle, with the ability to simultaneously observe 75 object + sky targets. It thus offers a huge multiplex advantage, compared with surveys utilizing single object spectroscopy – of which the largest to date is the work of Tresse et al. (2002), which surveys a total of 33 galaxies. Controlled selection of our targets ensures an accurate knowledge of the completeness of our survey. The selection function will be discussed in a future paper (Doherty et al., in preparation).

In this paper, we focus on the Hz detections from our pilot study of galaxies at $z \sim 1$ in the HDF-N with CIRPASS. The layout of the paper is as follows: in Section 2 we describe the instrument and our observations and in Section 3 we detail the data reduction techniques employed. In Section 4 we present results for a subsample of objects, which constitute our brightest detections of Hz (with $S/N > 5$), and use the results to derive the star formation rates in these redshift one galaxies, comparing these with that inferred from the rest-frame UV (2400 Å) continuum. Our conclusions are presented in Section 5.

In this paper we adopt the standard ‘concordance’ cosmology of $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, and use $h_{70} = H_0/70$ km s$^{-1}$Mpc$^{-1}$. AB magnitudes (Oke & Gunn 1983) are used throughout.

## 2 OBSERVATIONS

We performed multi-object spectroscopy of galaxies in the vicinity of the HDF-N with CIRPASS, a near-IR fibre-fed spectrograph operating between 0.9 and 1.67 μm. The upper cut-off is set by a blocking filter which reduces the thermal background. These HDF-N observations were undertaken at the Cassegrain focus on the 4.2-m William Herschel Telescope (WHT) in La Palma. The instrument was used in multi-object mode, with 150 fibres of 1.1-arcsec diameter on the sky (comparable to the expected seeing convolved with typical galaxy profiles). These fibres are deployable over an unvignetted field of diameter 15 arcmin. We used the FOCAP mechanism developed by the Anglo-Australian Observatory (AAO) as an interface to the telescope, with holes drilled in a brass plate to hold fibres in position. We acquired the field using six guide bundles, each containing seven closely packed fibres, centred on bright stars. We thus centroided the plate to an accuracy better than 0.5 arcsec, that is, less than half the fibre size.

A Hawaii 2K detector was used, and a grating of 831 line mm$^{-1}$, producing a dispersion of 0.95 Åpixel$^{-1}$. The full width at half maximum (FWHM) of each fibre extends over 2.7 pixel in both the spatial and spectral domain. The wavelength coverage was 1726 Å, covering most of the J-band, and the grating was tilted to set a central wavelength of $\lambda_c = 1.25 \mu$m. The resolving power was $R = \lambda_c/\Delta \lambda_{\text{FWHM}} \approx 5000$. At this resolution the background is very dark between the OH sky lines in the J- and H-bands, with only about 10 per cent of the area contaminated by skylines. By targeting galaxies with redshifts which place the Hz emission lines between the skylines, we become very sensitive to line emission – indeed, we are limited by the instrument background (although it is cooled to $\sim 42^\circ$C) rather than the sky. We targeted 65 objects using pairs of fibres offset by 6 arcmin, nodding the telescope between the A and B positions such that the fibre pairs alternately received light from the target object and sky. The 2D data frames are then subtracted directly from each other before extracting the spectra, so that sky subtracted off has been observed down the same fibre as the object. Although the sky background varies a lot on time-scales equivalent to our exposure time, we achieved reasonable first-order sky subtraction. Some low throughput fibres were not allocated positions. A total of 12 h integration time was obtained, over three nights, with individual integrations of 30 or 40 min per pointing. The array was read out non-destructively every 10 min, with three or four such loops per pointing to allow for cosmic ray rejection. There were 10 reads per each 10-min loop to reduce the readout noise, ensuring that we achieved background-limited observations.

The majority of our targets in this field were selected from the redshift survey of the HDF-N and ‘flanking fields’ carried out by Cohen et al. (2000), which is $>92$ per cent complete to $R_{AB} = 24$ for objects in the HDF-N proper and $R_{AB} = 23$ in the flanking fields. We selected all $R_{AB} < 24.5$ targets within the redshift range $0.73 < z < 1.0$ which fell within our 15-arcmin unvignetted field of view. A handful of objects were removed because of the limit on the fibre spacing (a minimum of 20 arcsec). We redefined the coordinates of our targets based on the GOODSv1.0 system (Giavalisco & GOODS Team 2003), for consistency in our astrometry between the

| id     | name          | RA (J2000) | Dec. (J2000) | $\lambda_{\text{Hz}}$ (Å) | $\xi_{\text{opt}}$ | $\xi_{\text{Hz}}$ | FWHM (Å) | Vel. FWHM (km s$^{-1}$) | flux $\times 10^{-16}$ (erg s$^{-1}$cm$^{-2}$) |
|--------|---------------|------------|-------------|--------------------------|-------------------|------------------|-----------|--------------------------|------------------------------------------|
| (a)    | J1236175+6214027 | 12 36 17.536 | +62 14 02.70 | 11924 | 0.818 | 0.8169 | * | * | 3.60 ± 5.58 |
| (b)    | J1237063+6215185 | 12 37 06.293 | +62 15 18.50 | 12078 | 0.84 | 0.8404 | 5.9 | 127 | 3.31 ± 0.38 |
| (c)    | J1237084+6215150 | 12 37 08.381 | +62 15 15.04 | 12074 | 0.839 | 0.8398 | 11.1 | 259 | 3.01 ± 0.54 |
| (d)    | J1237087+6211285 | 12 37 08.659 | +62 11 28.52 | 12520 | 0.907 | 0.9077 | 5.8 | 124 | 2.54 ± 0.34 |
| (e)    | J1237141+6210448 | 12 37 14.141 | +62 10 44.78 | 11952 | 0.821 | 0.8212 | 4.8 | 97 | 2.27 ± 0.36 |
| (f)    | J1237166+6210424 | 12 37 16.631 | +62 10 42.36 | 11949 | 0.821 | 0.8207 | 6.6 | 146 | 1.78 ± 0.40 |
| (g)    | J1237167+6213105 | 12 37 16.716 | +62 13 10.54 | 12465 | 0.898 | 0.8993 | 5.5 | 116 | 2.63 ± 0.31 |
targets and the alignment stars. The completeness of our sample is discussed in Doherty et al. (in preparation). In this paper we present observations of the seven sources in HDF-N where Hα was detected at more than $5\sigma$. These sources are all in the Cohen et al. (2000) flanking field, with $R_{AB} < 23.0$.

3 DATA REDUCTION

Data reduction was performed under IRAF with the CIRPASS package. For each multiple read exposure, the average of each loop was subtracted from the average of the next loop of non-destructive reads to form subintegrations of 10 min each at the same pointing. These subintegrations were then averaged together using the CRREJECT algorithm to reject cosmic ray strikes (using limits of $3\sigma$ according to gain and read-noise). The frames were then beam-switched by taking A–B pairs (providing first-order sky subtraction). We then subtracted off the average residual bias, determined from the unilluminated region of the array (the bias level of infrared arrays is known to float with time). The spectrum in each fibre was then optimally extracted according to the prescription of Johnson, Dean & Parry (2002), that is, the fibres were profile fitted in triplets (central fibre and two adjacent fibres) and the pixel values weighted and summed. This removes the contribution from the two adjacent fibres to the central fibre. This process produced positive (object–sky) and negative (sky–object) fibre pairs.

Dome flat-fields were also optimally extracted and used to correct variations in the fibre throughput and the spectral response of pixels on the array. Wavelength calibration was performed using an argon arc, fitting 30 lines with a third order polynomial, resulting in an rms dispersion of 0.1 Å. The spectra were then rectified to lie on a common wavelength scale.

In order to remove sky residuals which did not fully subtract out in the beam-switch, a low-order polynomial was fitted and subtracted along each rectified column of the flat-fielded, extracted spectra. This removed residuals due to temporal variation of the night sky spectrum. Flux calibration was carried out using observations of a $J = 10.68$ mag star from 2MASS which was placed on the same HDF-N plate as our targets. As it was thus observed simultaneously, this also corrects for temporal changes in the seeing, which fluctuated a lot over the course of the observations. As a consistency check we looked at six bright stars placed on the plate in another field from the survey. The fluxes were consistent to within 3 per cent, comparing the counts in our CIRPASS spectra with those predicted from the 2MASS J-band magnitudes.

In an average fibre, between skylines, for a spectrally unresolved line ($<60$ km s$^{-1}$) we achieve a sensitivity of $7.2 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ at $5\sigma$ in 3 h. However the emission lines we detect are typically broader than this ($\sim$100–250 km s$^{-1}$, Table 1).

4 RESULTS

In this paper we analyse a subsample of our HDF-N data: those galaxies with strongly detected (greater than $5\sigma$) Hα emission. These emission line spectra are shown in Fig. 1. The spectrum of the night sky is overlaid in dotted lines, giving a clear indication of the positions of skyline residuals, where the noise is significantly higher due to the enhanced background counts. These residuals do not adversely affect the data as the emission lines shown here all fall well between skylines. The dashed line shows the expected position

\footnote{http://www.ast.cam.ac.uk/~optics/cirpass/docs/install_cirp_software.html}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{spectra.png}
\caption{Spectra for the seven brightest Hα detections in our sample. The expected position of Hα at the optical spectroscopic redshift is marked with a dashed line. The sky spectrum is overlaid in dotted lines. The emission lines all fall well between sky lines.}
\end{figure}
for Hα, given the optical spectroscopic redshift. The centroid of Hα is accurate to 2 pixel (≈ 2 Å), so the error on the redshift is less than 0.001. There is agreement at this level with the optical redshifts given in Cohen et al. (2000) and which are listed in column 5 of Table 1.

We accurately measured the integrated line fluxes by measuring between zero power points (Table 1), having first subtracted off a continuum fit derived from regions adjacent to the emission line and unaffected by skylines. We checked our flux measurements by also fitting gaussian profiles to the lines, finding consistent values. The gaussian fits also gave the FWHMs for each line (Table 1). After subtracting the instrumental resolution in quadrature from the galaxy line widths, we find velocity FWHMs for these galaxies in the range ~100–250 km s⁻¹, equivalent to σ(ID) = 40–100 km s⁻¹. We note that some of this velocity width may be due to galactic rotation in the extended galaxies (galaxies J1236175+6214027, J1237084+6215150 and J1237166+6210424 are the most spatially extended and also exhibit the broadest lines).

The Hα luminosity of a galaxy is directly proportional to the ionizing flux from massive stars, which drops off very quickly, about 20 million years after star formation ceases. Hα thus traces the instantaneous star formation rate, whereas the UV luminosity evolves in time with the changes in stellar population and continues to rise even after star formation has ended. Because the Hα flux is proportional to the number of OB stars, in order to extrapolate to a total star formation rate (SFR) it is necessary to assume an initial mass function (IMF), and the conversion from Hα flux to SFR is quite sensitive to the IMF assumed (see discussion in Glazebrook et al. 1999). We use Kennicutt (1998) conversion which assumes a Salpeter IMF with 0.1 M⊙ < M < 100 M⊙:

\[ \text{SFR}(M⊙ \text{ yr}^{-1}) = 7.9 \times 10^{-42} L_{\text{Hα}}(\text{erg s}^{-1}) \]  

(1)

The derived SFRs of the galaxies are shown in Table 2, and in Fig. 2 we show B-, V-, i'- and z'-band images from HST/ACS taken from GOODSv1.0 (Giavalisco & GOODS Team 2003). We performed photometry on these images with 1-arcsec apertures, for consistency with our IR fibre size. In most cases the 1-arcsec fibres enclose most of the B-band light. However, for three of the sources (galaxies J1236175+6214027, J1237084+6215150 and J1237166+6210424) some fraction (<20 per cent) is missed. We reiterate that we have compensated for the effects of seeing by placing one of the fibres on a bright star in the field (thus observing the star simultaneously with the galaxies). This allows us to correct the flux calibration for seeing-dependent aperture losses.

We used the B-band magnitudes (4500 Å) to calculate rest-frame UV (2400 Å) flux densities and corresponding star formation rates. These are also shown in Table 2. For consistency, we also use the conversion given in Kennicutt (1998):

\[ \text{SFR}(M⊙ \text{ yr}^{-1}) = 1.4 \times 10^{-28} L_{\nu}(\text{erg s}^{-1} \text{ Hz}^{-1}) \]  

(2)

assuming the same IMF as used when deriving SFRs from the Hα flux (equation 1). The UV SFR relation also assumes continuous star formation over ~10⁸ yr.

Fig. 3 shows the SFRs for each galaxy calculated using the UV luminosity density and the Hα flux; those calculated from the UV luminosity densities are a factor of two lower, on average, than those from Hα. This is probably due to the differential effect of dust extinction in the redshift one galaxies between A_V ≈ 2400 and 6563 Å. This is consistent with results obtained by Glazebrook et al. (1999), Tresse et al. (2002), and Yan et al. (1999) who all find SFR(Hα)/SFR(UV) ratios of around 2–3.

There is no uniform correction that can be applied to the SFR estimated from UV flux in order to derive the true star formation rate: the amount of extinction varies in each object due to inherent differences in physical properties of the galaxies (e.g. Sullivan et al. 2001). As can be seen in Fig. 3, the statistical errors in our Hα flux measurements are not great enough to account for the scatter, which instead is attributable to different dust extinctions in our galaxy sample. Hα provides a more robust indicator for SFR, giving an independent estimate that is much less affected by dust obscuration. The ratio of the total SFR_Hα to SFR_UV for this subsample is 2. This fraction is potentially biased high, as there is a selection effect in this subsample due to the fact that we are only including the sources with strong detections of Hα; we will address the full R-band magnitude-limited sample in a future paper.

We now estimate the true star formation rate for each galaxy, assuming that the Kennicutt (1998) relations for Hα and UV SFRs should yield the same extrinsic SFR in the absence of extinction (i.e. assuming a Salpeter IMF and continuous star formation). Furthermore, we assume a Calzetti dust extinction law, appropriate for starburst galaxies (Calzetti 1997). For each galaxy we calculate the reddening value E(B − V) which gives the observed SFR(Hα)/SFR(UV) ratio. In Table 2 we list the reddening values derived and use these to compute the total dust corrected star formation rates. These are typically 50 per cent higher than those based purely on Hα, corresponding to an average E(B − V) = 0.16. Hence surveys based solely on UV (e.g. 2400 Å) continua (without dust correction) will underestimate SFRs at redshift one by factors of ≈2–11.

5 CONCLUSION
We have performed multi-object, near-infrared spectroscopy of z ~ 1 galaxies in the HDF-North, using CIRPASS-MOS. These
observations are part of an ongoing survey to trace star formation rates at redshift one. We have presented our brightest detections of \( \text{H} \alpha \) from three hours of observing time, as a demonstration of the success of this technique. We have shown that we can detect \( \text{H} \alpha \) at sufficient signal-to-noise ratio to obtain a good estimate of star formation rates in these galaxies. By pre-selecting galaxies with \( \text{H} \alpha \) redshifted between the OH sky lines, we can detect star formation rates of \( 5 \, h_{70}^{-2} \, M_\odot \, \text{yr}^{-1} \) (5\( \sigma \) in 3 h). The star formation rates obtained are higher than those estimated from UV continuum by a factor of about 2, due to dust obscuration in the UV. This is consistent with
previous work in this area. We have another \(~\sim\) 60 sources in this field, at known redshifts, therefore by stacking the spectra we will be able to obtain a global star formation rate for \(z \sim 1\) galaxies in the vicinity of the HDF-N. Between this and other fields we hope to build up a sample of several hundred galaxies which will allow us to determine the \(H\alpha\) luminosity function at \(z \sim 1\) and hence address the true star formation rate at this important epoch. The success of our pilot multi-object spectroscopic survey bodes well for future instruments, such as FMOS on Subaru.

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