On near-infrared Hα searches for high-redshift galaxies *

A. J. Bunker,1 S. J. Warren,1 P. C. Hewett2 and D. L. Clements1

1 University of Oxford, Department of Physics, Astrophysics, Keble Road, Oxford OX1 3RH
2 Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

Accepted 1994 November 1. Received 1994 September 2; in original form 1994 June 14

ABSTRACT

The lack of success of Lyα searches for high-redshift z > 2 field galaxies may be due to extinction by dust, suggesting that surveys based on lines of longer wavelength, particularly Hα, may be more effective. To test the dust hypothesis we have undertaken deep broad- (K′) and narrow-band (5000 km s−1, λ = 2.177 μm) imaging of the field towards the quasar PHL957, in an attempt to detect Hα emission from a known galaxy of redshift z = 2.313. We cover an area of 4.9 arcmin2 (0.28h−2 Mpc2) to a 4σ limiting narrow-band flux f = 2.7 × 10−16 erg cm−2 s−1, a factor of several deeper than previously published surveys. We detect the Hα+[N ii] emission line in this galaxy at the 3.3σ level, inferring a star formation rate of 18h−2 M⊙ yr−1. This is a factor only a few times larger than the rate seen in some Sc galaxies today. The faint flux level reached in this work demonstrates the promise of narrow-band imaging in the near-infrared as a technique for finding normal galaxies at high redshifts.

Key words: galaxies: formation – quasars: absorption lines – quasars: individual: PHL957

1 INTRODUCTION

Blank-sky searches for high-redshift field galaxies (z > 2) through the detection of the Lyα emission line (de Propris et al. 1993; Thompson et al. 1993) have so far had no success. These surveys span the redshift range 2 < z < 5, where galaxies may be experiencing their peak star formation rate (SFR), and now cover sufficiently large areas and reach such faint flux limits that they are in conflict with some theories (Djorgovski, Thompson & Smith 1993). Two competing explanations for the lack of success are (i) galaxies formed at higher redshift still (but note the unsuccessful search of Parkes, Collins & Joseph 1994), or (ii) the Lyα emission is severely attenuated due to extinction by dust, possibly exacerbated by resonant scattering from H i (Charlot & Fall 1991; Valls-Gabaud 1993). Surveys based on the detection of lines at longer wavelengths, especially [O ii] λ3727, Hβ λ4861, [O iii] λ5007, and Hα λ6563, benefit from greatly reduced extinction, allowing a test of the dust extinction hypothesis. The Hα line, which lies in the K-band at redshifts 2.08 < z < 2.66, is particularly useful because it provides a direct estimate of the SFR (Kennicutt 1993).

Thompson, Djorgovski & Beckwith (1994) have undertaken a pilot project for a near-infrared narrow-band imaging survey. They used a bandwidth of 4000 km s−1, and their deepest fields reach 4σ detection limits in the range 1 − 3 × 10−15 erg cm−2 s−1, over a total area of 0.3 arcmin2. Here we report the results of a similar pilot project, using a filter of width 5000 km s−1, which reaches much greater depth, 2.7 × 10−16 erg cm−2 s−1 (4σ), and covers a considerably larger area, 4.9 arcmin2. We have targeted the field of the quasar PHL957 (RA 1°00′33.4”, Dec. = 13°00′11.7”, 1950.0), zm = 2.681. Our aim was to detect Hα emission from the known high-redshift galaxy in this field, zm = 2.313, hereafter referred to as C1, which was found by Lowenthal et al. (1991). This galaxy lies at the same redshift as a damped Lyα absorption line seen in the spectrum of the quasar, and in fact was discovered in a narrow-band Lyα search for companions of damped system. This field therefore is particularly interesting as it may contain other detectable companions of these two objects.

2 OBSERVATIONS

Our broad- and narrow-band images of the field were obtained with the IRAC2B instrument on the 2.2-m telescope at the European Southern Observatory, over the three nights from 1993 October 31 to November 2. Conditions were photometric, and the seeing ranged between 0.7 and 1.2 arcsec. The detector for IRAC2B is a NICMOS3 2562 array. The pixel scale of 0.52 arcsec pixel−1 undersampled the seeing in the best conditions, but gave a large field of view, corre-

* Based on observations collected at the European Southern Observatory, La Silla, Chile
responding to 0.5 h$^{-1}$ Mpc comoving at the redshift of the galaxy C1.

The narrow-band filter used, ESO NB9, has a FWHM $\Delta \lambda_{\text{na}} = 0.038 \mu m$, and a central wavelength $\lambda_{\text{eff}} = 2.177 \mu m$, which closely matches the wavelength of H$\alpha$ for the galaxy. We used the ESO K′ filter for the broad-band observations. This filter is slightly narrower, $\Delta \lambda_{\text{K}} = 0.32 \mu m$, than the standard K filter, and shifted to a shorter wavelength, $\lambda_{\text{eff}} = 2.15 \mu m$, thereby reducing the sky/telescope thermal background by some 0.5 mag arcsec$^{-2}$. The observations comprised several sequences of duration 45 min, each made up of 9 individual 300-s frames, performed in a 3 × 3 grid pattern of step size 10 arcsec. Each 300-s frame was made up of a number of co-added exposures. The integration times of the individual exposures were 50 or 100-s for the narrow-band, and 10-s for the broad-band, and were chosen such that the sky counts ensured the observations were background limited, while staying well below the saturation count level. Total integration times were 405 min for the narrow-band, and 180 min for the broad-band. The average sky brightness was $m_{\text{na}} = 12.7$, $m_{\text{br}} = 13.1$ mag arcsec$^{-2}$.

From observations of standard stars we computed extinction and colour terms for both filters. All magnitudes quoted in this paper are in the natural system of the filters, zero-pointed to K, i.e. for a star of zero colour ($J - K = 0$) $m_{\text{na}} = m_{\text{br}} = K$. For the colour range of the standards used, $0.0 < J - K < 0.4$, the following equations apply:

\begin{align}
    m_{\text{na}} &= K + 0.07(J - K), \\
    m_{\text{br}} &= K + 0.13(J - K).
\end{align}

3 DATA REDUCTION

A dark frame of the appropriate integration time was subtracted from each data frame. The subsequent stages in the data reduction are division by flat field, and sky subtraction. The number of detected photons in an individual pixel is a sum of contributions from objects (O), the sky (S), and a thermal background (T) from the telescope and instrument. Before deciding on a method of data reduction it is important to investigate the nature of the spatial and temporal variations of S and T. To do this we first formed dome flats by creating normalized frames from the difference of exposures of the dome spot with and without illumination by a flat-field lamp. Since T is present in both frames it is removed in the subtraction, and the flat field created in this way should be about as good as a dome flat at optical wavelengths, i.e. an accuracy of a few per cent on large scales, and better on small scales. For large scales this was confirmed by an analysis of frames containing standard stars placed at different positions within the frame. The counts of the stars in the flattened frames show an rms variation of 2-3 per cent.

The data frames divided by dome flats show strong gradients across each frame, of magnitude typically 25 per cent of the mean count in the frame, which may be imputed to the thermal background. A comparison of frames taken at different times in the night shows that this background varies little with time, or with mean count level. For example the difference of two flattened frames taken 55 min apart, during which time the mean count level varied by 15 per cent, shows an rms variation of 0.3 per cent of the original mean count level. (This also provides an estimate the accuracy of the dome flat, i.e. better than 0.3/15 or 2 per cent.) We conclude that the background in our frames is characterized by two terms: (i) the night sky, which to first order is spatially flat, but temporally variable, at the level of a few per cent from frame to frame, and 20 per cent over the night, and (ii) the thermal radiation from the telescope and instrument, which to first order is temporally constant, but spatially variable, at the level of 25 per cent across the frame, and 1 per cent on the scale of a few pixels. There are additional contributions to the background, at the level of a few tenths of a per cent, in the form of arc-shaped and v-shaped patterns whose origin is unknown. These patterns are particularly pernicious because they exhibit both spatial and temporal variations. Fortunately, however, they vary smoothly both in position, on the scale of a few pixels, and in time, on the scale of a few frames.

It is common practice to use the frames themselves to flat-field infrared data. Since our data contain large gradients, this procedure would introduce systematic photometric errors equal to the magnitude of the gradients. Indeed, this was confirmed by an analysis of frames containing standard stars, flattened using data frames. The scatter in the standard-star photometry was considerably larger than that achieved with dome flats. For this reason we used dome flats for first-order flat fielding. Because the dome flats are accurate to a few per cent, which is the desired accuracy of the final photometry, it is irrelevant in practice whether the subsequent refinements to produce a flat sky background in each frame involve only subtraction, as pursued here, or a combination of division and subtraction, i.e. first obtaining a perfect flat field, followed by sky subtraction.

The sky, thermal, and pattern contributions were removed from each flat-fielded data frame in three stages. First the large-scale background was removed by subtracting a heavily median-filtered version (35 × 35 box) of the frame itself. The frames were then stacked, and the median of the stack was subtracted from each frame. This operation removes the average of the flat-field residuals as well as small-scale variations in the thermal background, due, for example, to dust on the dewar window. Finally a filtered version of the data cube was subtracted, using a 5 × 5 × 5 box. This process removes the patterns, as well as any remaining background (thermal, or flat-field residuals) that varies slowly with time. The dimensions of the filter were the subject of experimentation to optimize the final results, as quantified by the noise in the final combined frames, as well as the agreement of the photometry between images obtained on different nights. We found that a cubic box produced better results than a one-dimensional box (e.g. 1 × 1 × 9). This is because the x, y dimensions are similar to the scale of the patterns, and (presumably) because the ratio of the dome flat and the true flat field is smooth over these scales. Roughly speaking, the accuracy of the flat-field and sky subtraction processing is the product of the small-scale accuracy of the dome flat (∼ 1 per cent per pixel) and the

\footnote{We assume a cosmology with $h = H_0/100$ km s$^{-1}$ Mpc$^{-1}$, and $q_0 = 0.5$ unless otherwise stated.}
short-term variability of the sky level relative to the long-
term trend (∼ 2 per cent). This product (∼ 0.02 per cent
per pixel) is smaller than the Poisson error for a single frame
(e.g. ∼ 0.1 per cent per pixel for $K'$).

A second approach to the flat-fielding and sky subtrac-
tion used regression fits to the data, and solved, in an itera-
tive manner, for the three functions, via the flat field $F(x, y)$, the
thermal contribution $T(x, y)$, and the sky level $S(t)$. This
approach produced very similar results.

The reduced frames were registered, scaled (to account
for variations in the airmass), and then co-added, weight-
ing by the inverse of the scaled sky variance, while using a
percentage clipping algorithm to remove any discrepant
data points, due for example to cosmic-ray strikes. Bad pix-
els flagged in a mask frame (1 per cent of all pixels) were
ignored in the co-addition.

The dithering employed means that the edge regions of
the mosaiced final images have a greater noise level, since
fewer data frames contribute than in the central region of
common overlap. Therefore we trimmed the mosaiced im-
ages to the central 256 × 256 pixel region. The noise in the
sky is uniform over most of this region, but rises slightly to-
wards the edges. The final broad- and narrow-band images
are shown in Fig. 1.

4 RESULTS

To search for candidate high-redshift galaxies we performed
aperture photometry, with a radius $r = 3$ pixels (1.56 arc-
sec), on all objects visible in the narrow-band frame, and
selected the 30 objects detected at signal-to-noise ratio > 4
for subsequent photometry in the broad-band frame. The
measured magnitudes were converted to approximate total
magnitudes using an aperture correction measured from the
brightest objects. It is convenient to scale the frames to the
same zero-point, such that the relation between total ap-
parent magnitude $m$ and counts within the aperture $C$, for
both frames, is given by

$$m = 25 - 2.5 \log_{10} C. \tag{3}$$

The measured noise in the sky in the central regions of
the scaled frames is then $\sigma_{na} = 8.60$ counts pixel$^{-1}$, and
$\sigma_{br} = 3.95$ counts pixel$^{-1}$, which is close to the Poisson
limit, and corresponds to $m_{na} = 22.0$ mag arcsec$^{-2}$ and
$m_{br} = 22.8$ mag arcsec$^{-2}$. The 4σ detection limit is $m_{na} =
19.3$, or a narrow-band flux $f = 2.7 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$.

The results of the photometry are shown in Fig. 2 which
plots the $m_{br} - m_{na}$ colour versus narrow-band magnitude
$m_{na}$. The typical colour of objects in this plot is $m_{br} - m_{na} \sim
0.1$. This suggests that most of the objects are of rather late
stellar spectral type, for example cool stars, or elliptical
galaxies. Objects in the redshift range $2.29 < z < 2.35$ with
strong H${\alpha} + [N\, II]$ emission lines will lie above the sequence
of normal objects. The galaxy C1 itself lies at the top of Fig.
2. The measured magnitudes and colour for this galaxy are
provided in Table 1. The object is detected at 4.5σ in the
narrow-band, but is very faint in the broad-band (1.9σ).

To select candidate high-redshift galaxies we quantify
the significance of the excess flux in the narrow-band by
computing a parameter $\Sigma$, which is the number of standard
deviations between the counts measured in the broad-band
and the number expected on the basis of the narrow-band
counts. Where an object is extremely faint in the broad-
band, the error-parameter $\Sigma$ is well-defined even in cases
where the integrated counts within the registered aperture
are negative, and $m_{br}$ is undefined. In computing $\Sigma$ we
assume that only the noise in the sky contributes to the errors.
For simplicity we suppose zero colour $m_{br} = m_{na}$, which
may be approximately correct for the continuum of a high-
redshift galaxy. Lines of constant rest-frame equivalent
width $EW_{rf}$ are plotted in Fig. 2, computed from the relation

$$EW_{rf} = \frac{\Delta \lambda_{br} \Delta \lambda_{na} [1 - 10^{-0.4(m_{br} - m_{na})}]}{\Delta \lambda_{br} 10^{-0.4(m_{br} - m_{na})} - \Delta \lambda_{na}} \left[1 + \frac{z}{1 + z} \right] \tag{5}$$

For C1 we measure $\Sigma = 3.3$, and $EW_{rf} = 1190$ Å, with
a 2σ lower limit $EW_{rf} > 220$ Å, confirming that we have
detected the H${\alpha} + [N\, II]$ line from this galaxy. The measured
H${\alpha}$ line flux and estimated SFR are provided in Table 1. The
H${\alpha}$ line flux is calculated from the relation

$$f_{H\alpha} = \frac{\Delta \lambda_{br} [1 - 10^{-0.4(m_{br} - m_{na})}] 10^{-0.4(m_{br} + 19.57)}}{\Delta \lambda_{br} - \Delta \lambda_{na}} 1.33 \tag{6}$$

where the first term corrects for the contribution of the con-
tinuum to the narrow-band flux, and the second term con-
verts from magnitude to flux and corrects for the contribu-
tion of [N II], adopting the median ratio of $f_{[N\, II]/f_{H\alpha}} = 0.33$
found by Kennicutt and Kent (1983) for extragalactic H II
regions. To estimate the SFR we adopt the prescription of
Kennicutt (1983):

$$SFR = \frac{L(H\alpha)}{1.12 \times 10^{41} \, \text{erg s}^{-1}} M_{\odot} \, \text{yr}^{-1}. \tag{7}$$

For $z = 2.313$ the following relation applies, for different val-
ues of $q_{0}$:

$$SFR = 1.76 \times 10^{17} f_{H\alpha} h^{-2} M_{\odot} \, \text{yr}^{-1}(q_{0} = 0.1), \tag{8}$$

$$SFR = 8.56 \times 10^{16} f_{H\alpha} h^{-2} M_{\odot} \, \text{yr}^{-1}(q_{0} = 0.5). \tag{9}$$

### Table 1. Properties of galaxy C1.

| Offset rel. to PHL957 | 42.60°W, 24.1°N |
|----------------------|-----------------|
| $m_{na}$            | 19.22 (4.5σ)    |
| $m_{br}$            | 20.99 (1.9σ)    |
| $m_{br} - m_{na}$   | 1.77            |
| Colour significance $\Sigma$ | 3.3            |
| $EW_{H\alpha} + [N\, II]$ | > 220 Å (2σ) |
| $f_{H\alpha}$ | $2.1 \pm 0.6 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ |
| SFR $q_{0} = 0.1$ | $36 \pm 10 h^{-2} M_{\odot} \, \text{yr}^{-1}$ |
| SFR $q_{0} = 0.5$ | $18 \pm 5 h^{-2} M_{\odot} \, \text{yr}^{-1}$ |
Figure 1. Narrow-band ($\lambda = 2.177 \mu$m, upper) and broad-band ($K'$, lower) images of the field towards the quasar PHL957. North is up and east is to the left. The central $256 \times 256$ (133 × 133 arcsec$^2$) region of each mosaicked frame is shown. The broad-band frame reaches 0.8 mag deeper than the narrow-band frame, but the object C1, a known galaxy at $z = 2.313$, is brighter in the narrow-band frame due to the H$\alpha$+[N II] emission line.
Figure 2. Colour-magnitude diagram for the 30 objects detected in the narrow-band frame at signal-to-noise ratio > 4. The dashed lines are lines of constant $\Sigma$, which is the number of stars in the narrow-band frame at signal-to-noise ratio $> \text{75}\,\text{Å}$.

In fact the SFR is proportional to the significance $\Sigma$, so the lines of constant $\Sigma$ in Fig. 2 are lines of constant SFR. The line $\Sigma = 2$ corresponds to an SFR of $22 h^{-2} M_\odot \, \text{yr}^{-1}$ for $q_0 = 0.1$, and to $11 h^{-2} M_\odot \, \text{yr}^{-1}$ for $q_0 = 0.5$. In addition to C1 there are two other objects that lie above the lines $\Sigma = 2$ and $EW_{\text{H}\alpha} = 75 \, \text{Å}$ (although only just), i.e. their colours are consistent with their being galaxies at the same redshift as C1. The photometry for both objects, in both pass-bands, is consistent from night to night.

5 DISCUSSION

To summarize, we have undertaken a pilot study for a narrow-band H$\alpha$ near-infrared search for high-redshift galaxies. We have imaged a single field with an area of 4.9 arcmin$^2$, covering the redshift range $2.29 < z < 2.35$. Applying selection criteria of $EW_{\text{H}\alpha} > 75 \, \text{Å}$, SFR $> 11 h^{-2} M_\odot \, \text{yr}^{-1}$ there are three objects in the field whose colours are consistent with their being star-forming galaxies at the targeted redshift. One of the objects is a previously known galaxy (C1) of redshift $z = 2.313$, for which we measure an SFR $= 18 h^{-2} M_\odot \, \text{yr}^{-1}$. (If C1 harbours an AGN this is an upper limit to the SFR.) This is a factor of only a few times larger than the rate seen in some Sc galaxies today. Our successful detection therefore demonstrates the potential of the technique for finding normal galaxies at high redshifts. At a colder site and with a larger telescope, such as UKIRT using the new IRCAM3 instrument, we would reach a limiting flux a factor 2 to 3 fainter with the same integration times.

We can use our measurements of C1 to shed some light on the nature of this object, which is a candidate primeval galaxy. Lowenthal et al. (1993) measure $f_{\text{H}\alpha} = (5.6 \pm 0.0) \times 10^{-16} \, \text{erg cm}^{-2} \, \text{s}^{-1}$ and $V = 23.6$ for this galaxy. For a power-law spectral-energy distribution (SED), $f_\nu \propto \nu^\alpha$, the measured $K$-band continuum flux density corresponds to $\alpha = 0.1^{+0.6}_{-0.6}$, where the limits are 1$\sigma$. Therefore the SED is consistent with the flat SED $\alpha \sim 0$ expected for a young galaxy, but a deeper $K'$ image is needed to place better constraints. The measured H$\alpha$ flux from C1 of $(2.1 \pm 0.6) \times 10^{-16} \, \text{erg cm}^{-2} \, \text{s}^{-1}$ provides confirmation of the tentative spectroscopic detection by Hu et al. (1993) who found $(2.7 \pm 1.2) \times 10^{-16} \, \text{erg cm}^{-2} \, \text{s}^{-1}$ (where we have corrected their flux estimate for the contribution of [N II]). Therefore we confirm the conclusion of Hu et al. that extinction by dust of the Ly$\alpha$ flux from this galaxy is fairly modest. The ratio $f_{\text{H}\alpha}/f_{\text{Ly}\alpha} = 2.7$ compares with the low-density Case B value of 8.3, and implies a reddening $E(B-V) = 0.16$ (computed using the extinction law of Seaton 1979). This calculation assumes that resonant scattering is not significantly extend the escape path length of the Ly$\alpha$ photons. If, on the other hand, resonant scattering is important, the Ly$\alpha$ line is extinguished selectively relative to the continuum and the true rest-frame Ly$\alpha$ line EW could be substantially larger than the measured value of 140 Å. If this were the case the object would be classified as an AGN. By measuring the H$\beta$ line flux the true reddening could be measured, and the intrinsic Ly$\alpha$ line EW inferred.

While the Ly$\alpha$ line in C1 is not greatly affected by dust, this may not be true of most galaxies, given the lack of success of surveys for high-redshift galaxies. Therefore the faint flux level reached in the work reported here demonstrates the promise of narrow-band imaging in the near-infrared as a technique for finding normal galaxies at high redshifts. One of the two other possible high-redshift galaxies lies within the field surveyed by Lowenthal et al. (1993) for Ly$\alpha$ emission, but does not show evidence for strong Ly$\alpha$ emission. Infrared spectroscopy of this candidate and others detected in this way will provide a test of the hypothesis that extinction by dust is responsible for the lack of success of surveys for high-redshift galaxies.

ACKNOWLEDGMENTS

AJB and DLC acknowledge financial support from SERC/PPARC. SJW acknowledges a Royal Society University Research Fellowship. The authors wish to thank the staff at ESO, Chile, particularly Andrea Moneti for his help with the IRAC2B camera.

REFERENCES

Charlot S., Fall S. M., 1991, ApJ, 378, 471

de Propris R., Pritchet C. J., Hartwick F. D. A., Hickson P., 1993, AJ, 105, 1243

© 0000 RAS, MNRAS 000, 000-000
Djorgovski S., Thompson D., Smith J. D., 1993, in Akerlof C., Srednicki M., eds, Texas/PASCOS’92: Relativistic Astrophysics and Particle Cosmology. Ann. N. Y. Acad. Sci., 688, 515
Hu E. M., Songaila A., Cowie L. L., Hodapp K-W., 1993, ApJ, 419, L13
Kennicutt R. C., 1983, ApJ, 272, 54
Kennicutt R. C., 1993, ApJ, 388, 310
Kennicutt R. C., Kent S. M., 1983, AJ, 88, 1094
Lowenthal J. D., Hogan C. J., Green R. F., Cauet A., Woodgate B. E., Brown L., Foltz C. B., 1991, ApJ, 377, L73
Parkes I. M., Collins C. A., Joseph R. D., 1994, MNRAS, 266, 983
Seaton M. J., 1979, MNRAS, 187, 73P
Thompson D., Djorgovski S., Trauger J., Beckwith S. V. W., 1993, in Soifer B. T., ed, Sky surveys: Protostars to Protogalaxies. A. S. P. Conf. Series Vol. 43, p. 189
Thompson D., Djorgovski S., Beckwith S. V. W., 1994, AJ, 107, 1
Valls-Gabaud D., 1993, ApJ, 419, 7

This paper has been produced using the Royal Astronomical Society/Blackwell Science \LaTeX{} style file.
