First results from the Isaac Newton Telescope Wide Angle Survey: the z > 5 quasar survey

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ABSTRACT

We report the first results of an observational programme designed to determine the luminosity density of high-redshift quasars (z > 5 quasars) using deep multicolour CCD data. We report the discovery and spectra of three i < 21.5 high-redshift (z > 4.4) quasars, including one with z > 5. At z = 5.17, this is the fourth highest redshift quasar currently published. Using these preliminary results we derive an estimate of the $M_B < -25.0$ ($M_{AB1450} < -24.5$) quasar space density in the redshift range 4.8 < z < 5.8 of $3.6 \pm 2.5 \times 10^{-8}$ Mpc⁻³. When completed, the survey will provide a firm constraint on the contribution to the ionizing UV background in the redshift range 4.5-5.5 from quasars by determining the faint-end slope of the quasar luminosity function. The survey uses imaging data taken with the 2.5-m Isaac Newton Telescope as part of the Public Isaac Newton Group Wide Field Survey (WFS). This initial sample of objects is taken from two fields of effective area ~12.5 deg² from the final ~100 deg².

Key words: galaxies: active - quasars: general.

1 INTRODUCTION

The identification and study of quasars at high redshift provides key diagnostic information on the early Universe. Over the last few years the relationship between high-redshift quasars and local galaxies has been given an impetus from the realization that quiescent black holes may lie at the centre of all local bulges including the Milky Way (e.g. Magorrian et al. 1998). The formation and evolution of massive black holes is fast becoming a mainstream topic in theories of galaxy formation and evolution (Haehnelt, Natarajan & Rees 1998; Kauffmann & Haehnelt 2000).

High-redshift quasars are also an important contributor to the UV radiation field in the early Universe. Specifically the lack of an optically thick, Gunn-Peterson (Gunn & Peterson 1965) trough in the spectra of high-redshift objects (e.g. Songaila et al. 1999) implies that the Universe is highly ionized at $z \sim 5.5$. Estimates by Madau et al. (1999) indicate that if the ionization is caused by starlight then the inferred star formation rate at z = 5 must be comparable to or greater than the observed value at z = 3. The direct detection of galaxies at $z \sim 3$ via the Lyman Break technique and the detection of measurable Lyman continuum photons that escape these galaxies (Steidel, Pettini & Adelberger 2001) has raised a question over whether quasars or galaxies are the origin of the UV photons that re-ionized the Universe at z > 6. Recent theoretical work (Miralda-Escude et al. 1998; Madau, Haardt & Rees 1999)

*E-mail: rgs@ast.cam.ac.uk (RGS); rgm@ast.cam.ac.uk (RGM); mike@ ast.cam.ac.uk (MJI); sth@ast.cam.ac.uk (STH) indicates that a Gunn–Peterson trough should be present by $z \sim 6$. A major uncertainty in all of this work is the measurement of the ionizing background from quasars. The current uncertainty in the contribution of quasars to the UV background is predominantly caused by the unconstrained faint end of the luminosity function.

The resent discovery of several z > 5 quasars by the Sloan Digital Sky Survey (SDSS, Fan et al. 2001b) will constrain the bright end (i < 20.0) of the high-redshift luminosity function. We are undertaking a survey 1–2 mag fainter than the SDSS programme, with the aim of constraining the space density and evolution of lower luminosity quasars where the majority of the ionizing flux arises. In this paper we present results from the first ~10 deg² of our survey. Unless stated otherwise we use conventional Vega magnitudes and $H_0 = 50 \,\mathrm{km \, s^{-1} \, Mpc^{-1}}$, $q_0 = 0.5$.

2 SURVEY IMAGING DATA

We are using data from the Isaac Newton Telescope(INT) Wide Angle Survey (WAS) (McMahon et al. 2000; http://www.ast.cam. ac.uk/~wfcsur/). The survey is carried out with the prime focus Wide Field camera (WFC; Ives, Tulloch & Churchill 1996) at the 2.5-m INT. The WFC consists of a close packed mosaic of four thinned EEV42 $2k \times 4k$ CCDs, with a pixel size of $13.5 \,\mu\text{m}$ corresponding to 0.33 arcsec pixel⁻¹ and effective field of view of 0.25 deg². The survey consists of single 600-s exposures in 5 wavebands (*ugriz*) over an area ~100 deg² to a nominal 5σ limiting magnitude(Vega) of 23, 25, 24, 23 and 22 respectively.

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The CCD mosaic data from all survey runs is pipeline-processed in Cambridge (Irwin & Lewis 2000) to produce photometrically and astrometrically calibrated images [rms(internal) = 0.1 arcsec], and morphologically classified merged multicolour catalogues. A preliminary photometric calibration has been applied to the data to the ± 0.1 mag level. For the current work we have only used data with seeing of <1.67 arcsec [full width at half-maximum (FWHM) of 5 pixel] and stellar ellipticity (arising from trailing) of better than <0.2, because this defines a practical upper limit for reliable image morphological classification. The current quasar candidate sample has a magnitude limit of *i* or $z \ll 21$, the practical limit for acceptable signal-to-noise ratio spectra with a 4-m class telescope in 1800 s of observation.

At the time of the spectroscopic follow-up observations in 2000 June, object catalogues for data taken between 1998 August and



Figure 1. The *gri* and *riz* two-colour diagrams. Data from eight pointings $(\sim 2 \text{ deg}^2)$ of the INT WFS are shown. All objects are classified as stellar and have i < 21.5. The newly discovered quasars (overplotted as squares) sit apart from the stellar locus. A model colour evolution track for quasars is overlaid. Filled circles indicate a 0.2 step in redshift from the larger circle at a redshift of 4.8 in this model.

1999 October were available. This data is taken from two regions of the survey. The first region covers the ISO ELAIS N1 field at J1610+5430 (Oliver et al. 2000), the second region is in the vicinity of at J2240+0000. A total area of 12.5 deg² has been used.

3 COLOUR SELECTION OF CANDIDATES

Fig. 1 shows colour–colour plots for INT WFS data in the griz bands with the predicted quasar tracks as a function of redshift



Figure 2. Quasars are readily identified, even at low signal-to-noise ratio, by the characteristic continuum break across the prominent Lyman α emission line. The identification of low-level emission lines arising from O vI, Si IV and C IV at the correct wavelengths relative to Lyman α support the redshift estimation for these objects.

overplotted. These colour tracks were computed assuming an underlying quasar spectrum based on a power law with spectral index $S_{\nu} \propto \nu^{-0.5}$ and with an emission-line spectrum based on the composite spectrum of Vanden Berk et al. (2001). The absorption model for the intervening Lyman α forest is taken from Madau (1995). The stellar main sequence is clearly visible as the heavily populated strip in the centre of the plots.

Candidate high-redshift objects are selected from the multicolour data by selecting all objects that obey a set of colour criteria. To establish these criteria the stellar locus in the colour–colour diagrams has been approximated using piecewise linear fits in the colour space. These fits are then used to establish the boundaries indicated in Fig. 1.

Once selected by one of these colour criteria all 5 *ugriz* images of an object are then visually examined to check the validity of the photometry. This step is required to identify spurious sources such as objects in the diffraction spikes of bright stars or satellites and asteroids that have moved significantly between observations. Candidate $z \ge 5$ quasars are selected using the *riz* diagram whereas $4 \le z \le 5$ candidates are selected from the *gri* colour diagram. At the current time the follow-up of the lower redshift sample is incomplete owing to limited spectroscopic time.

4 SPECTROSCOPIC OBSERVATIONS

Spectroscopic observations were obtained over two nights (2000 June 29 and 30) using the red arm of the ISIS dual beam spectrograph on the 4.2-m William Hershel Telescope on La Palma. The R158R grating was used with the TeK4 CCD, giving a spectral resolution of 2.90 Å pixel⁻¹ and wavelength coverage of 2970 Å. Initially a central wavelength of 7900 Å was selected, but during observations it became apparent that a useful spectrum could not be taken of faint objects longward of 9000 Å owing to strong night-sky line emission, and so a central wavelength of 7500 Å was subsequently used.

The slit width was matched to the seeing, which varied over the course of the observing run in the range 0.8–1.2 arcsec. During the periods of poorer seeing (≥ 1 arcsec), brighter candidate objects were observed. These generally proved to be low-mass late M and early L stars as expected. Conditions were photometric throughout the run and observations of the spectrophotometric standards HZ 44, Ross 640 and LDS 749B (ING identifiers sp1321+363, sp1626+368 and sp2129+000) were used to flux-calibrate the

data. Wavelength calibration was carried out using a mixture of arc spectra and night-sky lines.

Each observation was taken as a series of 900-s exposures and coadded to improve cosmic ray rejection. Total exposure times range from 900–2700 s. Several candidate objects could be identified as late M and early L dwarf stars after only a single 900-s exposure. Observation of these objects was truncated reducing the time spent observing non-quasar candidates.

5 CONFIRMED HIGH-REDSHIFT QUASARS

The identification spectra of the confirmed high-redshift (z > 4.4) quasars are shown in Fig. 2 with finding charts derived from the *i*-band WFS images shown in Fig. 5. Photometry details and coordinates are given in Table 1 and the emission-line properties are presented in Table 2. Absolute *B* (Vega) band magnitudes and AB magnitudes at a rest-frame wavelength of 1450 Å have been determined from the *z*-band magnitudes assuming a power-law spectral index of -0.5. We use the *z* band, because it is unaffected by the Lyman α forest or any strong emission lines.

Redshift determination for high-redshift objects is complicated because in many spectra the only strong line visible is Lyman α (1215.7 Å). This is often blended on the red side with N v emission (1240.1 Å) in quasar spectra and has an asymmetric profile owing to absorption of the blue wing of the line by the Lyman α forest. The onset of this absorption of the blue wing of the line is quite abrupt and we take this as our redshift estimate for the quasars.

wfsj224524.2+002414. At z = 5.17, this is currently the fourth highest redshift quasar known. This faint object is identified by the strong Lyman α line at 7498 Å and the break in the continuum across the line resulting from Lyman α forest absorption. Lyman α shows a highly irregular profile with strong absorption features within the line. A strong absorption feature is also at the expected wavelength of N v emission redward of Lyman α .

wfsj161253.1+525543. This object shows a broad emission feature interpreted as a blend of Lyman α and N v. The wavelength of any associated C IV emission line is in a region of the spectrum heavily effected by emission from the night sky, making detection of an emission feature difficult. At z = 4.95 this quasar is the seventh highest redshift quasar known.

wfsj224531.0+003358. Strong Lyman α emission dominates the spectra of this object. Two clear absorption features,

Table 1. Photometry derived from the INT WFS.

				Vega system magnitudes							
Object	Z	RA (J2000) Dec.		и	g	r	i	z	$M_{\rm B}$	$M_{AB(1450)}$	
wfsj224524.2+002414 wfsj161253.1+525543 wfsj224531.0+003358	5.17 4.95 4.45	22 45 24.28 16 12 53.11 22 45 31.00	+00 24 14.6 +52 55 43.5 +00 33 58.6	>23.01 >23.00 >23.09	>24.89 >25.12 >24.89	23.96 22.21 21.60	21.43 20.15 20.87	21.19 19.89 20.36	-24.9 -26.1 -25.5	-24.3 -25.6 -25.0	

Tal	ble	2.	Emission-line	e properties.
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Object	z	Lyman α				Сту			
-		Peak (z)	Cent. (z)	EW _{obs}	EW _{rest}	Cent. (z)	EW _{obs}	EW _{rest}	
wfsj2245+0024 wfsj1612+5255 wfsj2245+0033	5.17 4.95 4.45	7498 Å (5.17) 7237 Å (4.95) 6628 Å (4.45)	7450 Å (5.16) 7318 Å (5.00) 6634 Å (4.46)	594 Å 470 Å 276 Å	115 Å 79 Å 51 Å	9112 Å (4.88) 8400 Å (4.42)	308 Å	52 Å	

characteristic of the class of broad absorption line (BAL) quasars, are seen associated with Nv and CIV emission lines.

The FIRST and NVSS radio surveys (Becker, White & Helfand 1995; Condon et al. 1998) cover our survey regions and no radio



Figure 3. The histogram of Lyman α equivalent widths for SDSS quasars with redshift z > 4.4 is shown with the measurements from the three z > 4.4 INT WFS quasars overplotted for comparison.

Table 3. Known high-redshift (z > 4.9) quasars.

Name	Z.	Mag				
		r	i	z	$M_{\rm B}$	
wfsj2245.6+0024	5.17	23.96	21.43	21.19	-24.9	1
wfsj1612.7+5255	4.95	22.21	20.15	19.89	-26.1	1
SDSS1044-0125	5.80	>22.83	21.40	18.67	-27.5	2
RD J0301+0020	5.50	26.2	23.38	22.84	-23.4	3
SDSSp J1208+0010	5.27	22.66	20.37	20.17	-26.0	4
SDSSp J1204-0021	5.03	20.72	18.89	18.56	-27.5	5
SDSSp J0338+0021	5.00	21.61	19.54	19.19	-26.8	6
SDSSp J1605-0112	4.92	22.42	19.36	19.37	-26.6	5
SDSSp J0211-0009	4.90	21.97	19.51	19.26	-26.7	6

Refs: (1) This work; (2) Fan et al. (2000b); (3) Stern et al. (2000); (4) Zheng et al. (2000); (5) Fan et al. (2000a); (6) Fan et al. (1999).



Figure 4. An estimate of the survey completeness is derived based on the model quasar spectrum described in the text. The fractional completeness is shown as a function of redshift The confirmed quasars are marked as black circles. At the current limiting magnitude the survey is not sensitive to photometric errors and so there is little change in completeness with magnitude.

emission with $S_{20 \text{ cm}} > 1 \text{ mJy} (5\sigma)$ is detected for these quasars. There is also no evidence for X-ray emission from *ROSAT* All Sky Survey or PSPC pointed phase observations.

Fig. 3 shows the equivalent width distribution of Lyman α for the SDSS z > 4.4 quasars compared with our new quasars. Despite the strength of the line in our z = 5.17 quasar, it is comparable with the strongest lined objects in the SDSS sample.



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Figure 5. Finding charts are taken from *i*-band images. The charts are 4.4 arcmin (800 pixel) square with the quasar marked by the cross-hair.

6 DISCUSSION AND CONCLUSIONS

The majority of the ~250 z > 4 quasars that are currently known (see http://www.ast.cam.ac.uk/~quasars) have been discovered using photographic plates, but despite the relative ease with which z > 4 quasars can be discovered (e.g. Storrie-Lombardi et al. 2000 and refs therein), for almost a decade the highest redshift object known was the optically selected quasar PC1247+3406 with z = 4.89 (Schneider, Schmidt & Gunn 1991). The addition of the z band to multicolour surveys has changed this. The first quasars with z > 4.9 was discovered by Fan et al. (1999) using SDSS data in the *griz* bands. In this paper we report two new quasars at z > 4.9, bringing the total sample of published quasars with redshift z > 4.9 to nine, of which six have $z \ge 5$ (see Table 3).

We use our sample to make the first estimate of the space density of low luminosity quasars at $z \sim 5$. Fig. 4 shows the completeness of our survey with redshift. At the current magnitude limit for the spectroscopic sample, the survey is not sensitive to photometric errors and so there is no magnitude effect on completeness. This has been computed using the approach described in Fan et al. (2001a) where we use the Madau (1995) intergalactic medium (IGM) absorption model and an intrinsic unabsorbed quasar spectrum with a power-law continuum spectrum with a gaussian distribution of spectral indices (mean = 0.5; dispersion $\sigma = 0.3$) and a contribution from emission lines. The relative emission-line strengths are taken from the SDSS composite quasar spectrum (Vanden Berk et al. 2001) normalized to a Lyman α line strength distribution (rest-frame equivalent width: Gaussian with mean 92.91 and sigma 24.0) from Wilkes (1986). Using this completeness, we calculate the effective volume assuming $H_0 =$ $50 \,\mathrm{km \, s^{-1} \, Mpc^{-1}}, q_0 = 0.5.$

The INT WFS is ongoing and to date ~ 10 per cent of the final survey imaging data has been investigated for candidate quasars. The final survey is expected to contain 10–20 high-redshift (z > 5) low-luminosity quasars (i < 21.5) and should therefore constrain the luminosity density to \sim 20 per cent. This statistically significant sample of low-luminosity quasars will allow the determination of the faint-end slope of the quasar luminosity function and the break point in the distribution (analogue to L^* for galaxies). This break point is required to allow estimation of the contribution of quasars to the ionizing UV background at high redshift. Our results, when combined with shallower surveys such as the SDSS, will allow detailed studies of the active galactic nucleus phenomenon at high redshift over a range of UV luminosities. Our knowledge of the relationship between accretion and the formation of black holes and galaxies will not then rely purely on the properties of the rare extreme-luminosity quasars.

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