

MULTICOLOR DETECTION OF HIGH-REDSHIFT QUASARS. II. FIVE OBJECTS WITH $z \geq 4$ J. D. SMITH, S. DJORGOVSKI,^{1,2} D. THOMPSON, W. F. BRISKEN, G. NEUGEBAUER, AND K. MATTHEWS

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ABSTRACT

We report the results of a multicolor wide-field CCD survey designed to rediscover several *BRI* quasars previously found in a photographic survey by Irwin *et al.* [ASPCS, 21, 117 (1991)], but not fully documented in the literature. Here we provide spectra, redshifts, finding charts, magnitudes, and coordinates for four such *BRI* quasars. Follow-up observations were obtained for BRI 2235–03, a borderline BAL object. A moderate resolution absorption line spectrum for the object shows a very dense Ly α forest and two C IV doublets at $z > 3$. Its visible spectrum is redder than those of the other quasars presented, although it is similar in the infrared. *J*, *H*, and *K* magnitudes are presented for this quasar, showing it to be one of the most luminous objects known. New *J*, *H*, and *K* photometry is presented for PC 1247+3406, the most distant quasar known. In the course of the survey we also discovered a new quasar with $z=4.042$. Its spectrum, coordinates, magnitudes, and finding chart are presented here as well.

1. INTRODUCTION

In the last few years, several groups have been successful in the search for high-redshift ($z > 4$) quasars, with over 40 such objects having been found to date (Schneider *et al.* 1991a, b; Warren *et al.* 1991; Irwin *et al.* 1991). These surveys have helped to give a better understanding of the quasar luminosity function as well as the origins of quasars themselves. Studies of the absorption line spectra of these objects also give valuable information on the nature and evolution of the intergalactic medium at high redshifts. The existence of $z > 4$ quasars is evidence of the formation of structure in the universe at early epochs (5–10 percent of its present age). Since these objects would have had only ~ 1 billion years to form and turn on, they must have collapsed from the highest peaks of the primordial density field. This places strong constraints on galaxy formation in the early universe (Rees 1992; Turner 1991).

Of the about 40 $z > 4$ quasars known, only 17 have pub-

lished coordinates. Irwin *et al.* (1991) have discovered over 20 such objects in a photographic multicolor survey using APM measurements of UK Schmidt Telescope plates, but have reported the coordinates for only two of these objects (McMahon *et al.* 1994; Williger *et al.* 1994). Rough coordinates for some of the *BRI* quasars are given by Irwin & McMahon (1990). We are conducting a multicolor survey for quasars and star forming galaxies near known $z \geq 4$ quasars, looking for protoclusters near these early quasars (Smith *et al.* 1993; Djorgovski *et al.* 1991). We are interested in using the *BRI* quasars in our protocluster search, and so began a survey to “rediscover” these objects. We have previously reported on two such objects (Smith *et al.* 1994). Here we present data on four more quasars: BRI 0103+00, BRI 0151–00, BRI 1500+08, and BRI 2235–03. One of these objects, BRI 2235–03, has a very red continuum, and we present infrared magnitudes and a moderate resolution absorption line spectrum of it as well.

During the course of the survey, we discovered a new $z > 4$ quasar in the field of BRI 0111–28. This quasar, designated QSO 0111–2838, has $R=19.75$, almost a full magnitude fainter than the stated limit of the Irwin *et al.* (1991) survey. We provide spectroscopy, coordinates, magnitudes, and a finding chart for this object.

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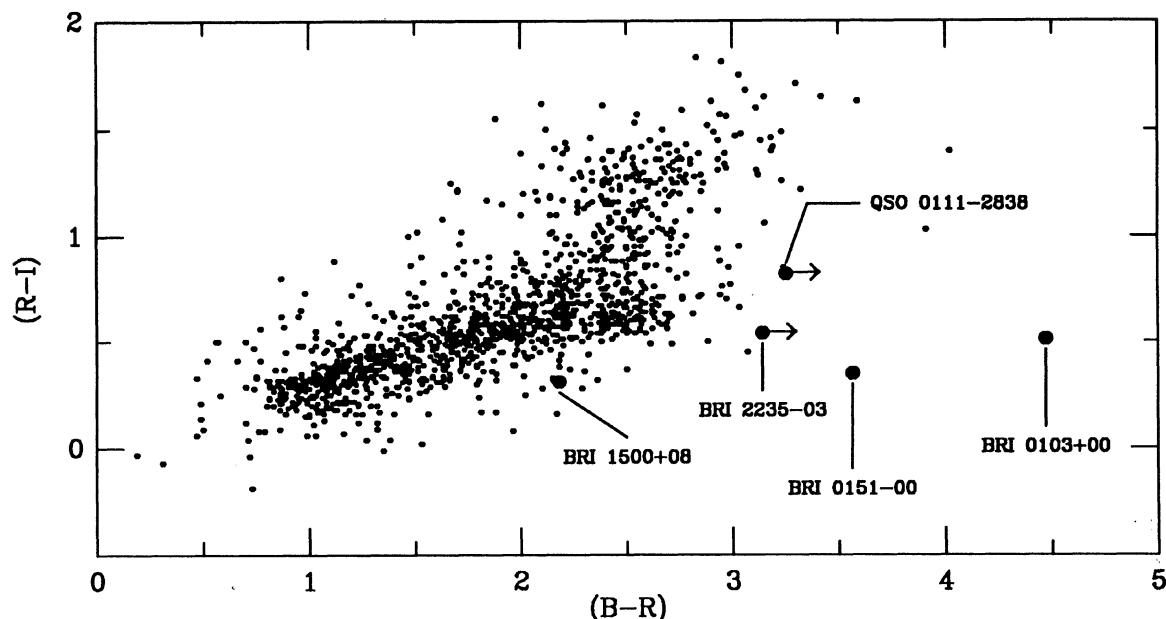


FIG. 1. The *BRI* color-color diagram of all objects with $14.0 < R < 20.0$ in a 15 arcmin square field containing the “rediscovered” *BRI* quasars and the new quasar QSO 0111–2838. Arrows designate that the $(B-R)$ color is a lower limit.

2. OBSERVATIONS AND RESULTS

2.1 Technique

Imaging techniques for this survey are covered in detail in Smith *et al.* (1994) and are only discussed briefly here. A simple method to discover high-redshift quasars is to use the *BRI* or Gunn–Thuan *gri* bands, and look for objects where the Ly α line is in the red band. The line, and the continuum drop across it would leave a distinct color-color signature.

The *BRI* quasars have coordinates published truncated to the nearest degree in declination and to the nearest minute in right ascension (Irwin & McMahon 1990). Our initial imaging data were taken at the CTIO Schmidt telescope using a 1024^2 Tektronix CCD giving a 31.2 arcmin field of view with 1.83 arcsec/pixel and at the Palomar 60 in. telescope using reimaging optics and a 1024^2 Tektronix CCD giving an 18.4 arcmin field of view with 1.08 arcsec/pixel. Three pointings in a strip of constant right ascension were necessary in order to cover the desired range with some overlap using the CTIO Schmidt while four pointings were necessary with the Palomar 60 in.

The imaging was obtained in the *BRI* or *BRI* bands. Photometry was performed on all objects in the fields using DAOPHOT (Stetson 1987) and calibrated using standard stars (Landolt 1992; Kent 1985). All objects with appropriate colors were visually examined and a candidate list was formed by ranking candidates according to their positions in color-color space and image morphology (stellar versus extended). Follow-up spectroscopy of our highest ranked candidates was then performed.

2.2 CCD Imaging and Astrometry

CCD imaging totaling 3600 s in *B*, 900 s in *R*, and 900 s in *i* was obtained under photometric conditions on the four

fields around BRI 1500+08 at the Palomar 60 in. telescope on the nights UT 1993 May 18–20. Our initial imaging from the CTIO Schmidt telescope consisted of two 300 s exposures in each of the *BRI* bands at the three pointings around BRI 0111–28 under photometric conditions and around BRI 2235–03 under nonphotometric conditions on UT 1993 June 26 and 29. A total of 1800 s in *B*, 400 s in *R*, and 400 s in *i* was obtained under photometric conditions on the four fields around BRI 0103+00 and BRI 0151–00 at the Palomar 60 in. telescope on the nights UT 1993 October 19 and 20. All of the data are complete to at least 20^m in *R* with the exception of the BRI 2235–03 data which are complete to 19^m . The combined color-color diagram of all the objects with $14 < R < 20$ in the fields containing the five quasars is shown in Fig. 1. The $(B-R)$ vs $(R-i)$ data from the fields around BRI 1500+08, BRI 0103+00, and BRI 0151–00 were shifted along the $(R-i)$ axes of the BRI 0111–28 data so that the stellar sequences coincide. The nonphotometric data of BRI 2235–03 were shifted so that its stellar sequence coincides with the BRI 0111–28 data as well.

Aperture photometry using the initial Palomar 60 in. data give $R = 18.70 \pm 0.09$ for BRI 0103+00, $R = 18.65 \pm 0.09$ for BRI 0151–00, and $R = 18.84 \pm 0.07$ for BRI 1500+08. Follow-up imaging of the four *BRI* quasars was performed at the Palomar 60 in. telescope using direct imaging in the Gunn–Thuan *r* band under photometric conditions on UT 1993 September 12–13 and December 10. Aperture photometry on these objects gives $r = 18.94 \pm 0.03$ for BRI 0103+00, $r = 18.76 \pm 0.03$ for BRI 0151–00, $r = 19.04 \pm 0.02$ for BRI 1500+08, and $r = 18.72 \pm 0.05$ for BRI 2235–03. Finding charts made from this follow-up imaging are shown in Fig. 2. *R* magnitudes are listed in Table 1.

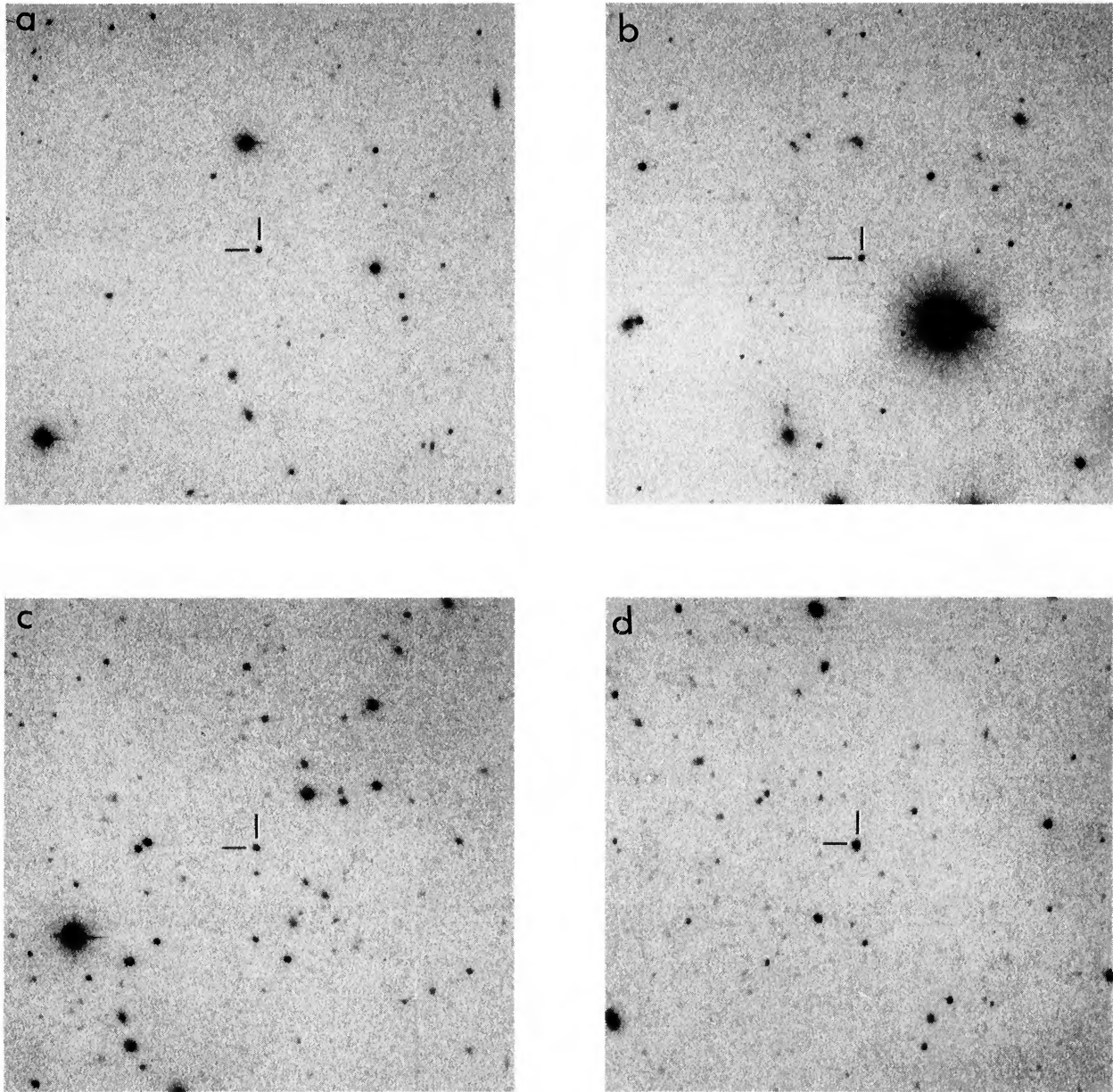


FIG. 2. Gunn- r band images of the four rediscovered *BRI* quasars taken with the Palomar 60 in. telescope. All images are 4 arcmin square with north up and east to the left. (a) BRI 0103+00, (b) BRI 0151-00, (c) BRI 1500+08, (d) BRI 2235-03.

TABLE 1. Coordinates, redshifts, R magnitudes, and continuum depressions, D_A , for the quasars.

QSO	α (B1950)	δ (B1950)	z	R	D_A
BRI 0103+00	01 03 45.3	+00 32 21	4.433 ± 0.005	18.70 ± 0.09	0.62
BRI 0151-00	01 51 05.9	-00 25 44	4.196 ± 0.005	18.65 ± 0.09	0.68
BRI 1500+08	15 00 18.2	+08 24 49	3.96 ± 0.02	18.84 ± 0.07	0.62
BRI 2235-03	22 35 47.5	-03 01 30	4.23 ± 0.02	18.6 ± 0.2	0.78
QSO 0111-2838	01 11 06.6	-28 38 15	4.042 ± 0.005	19.75 ± 0.10	0.52

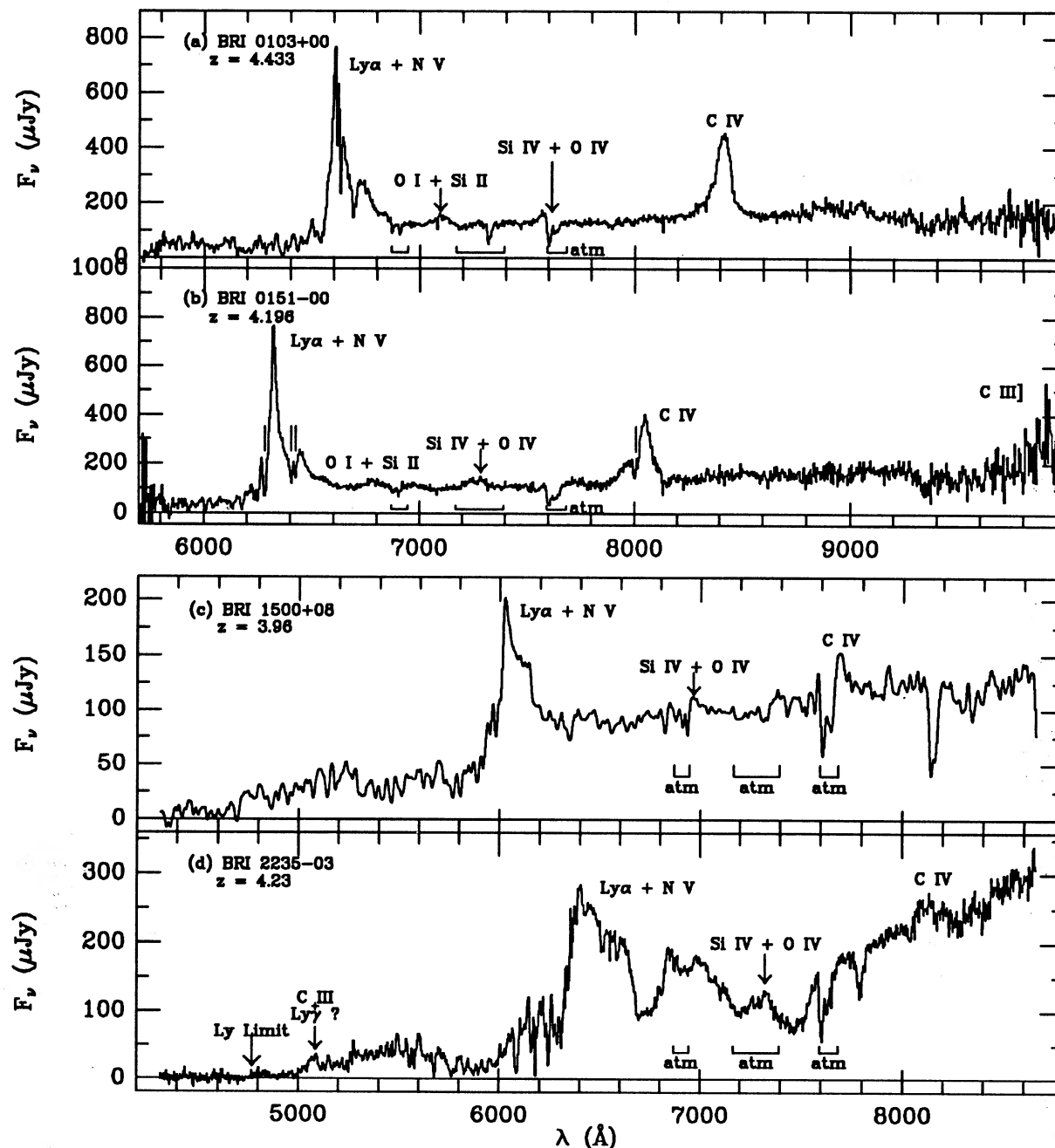


FIG. 3. Low resolution spectra of the four rediscovered *BRI* quasars taken with the EMMI spectrograph on the ESO NTT. (a) A 1500 s spectrum of BRI 0103+00 from UT 1993 December 8. (b) A 1200 s spectrum of BRI 0151-00 from UT 1993 December 9. (c) A 2700 s spectrum of BRI 1500+08 from UT 1993 August 19. The spectrum has been Gaussian smoothed with $\sigma=2$ pixels. (d) A 7200 s spectrum of BRI 2235-03 from UT 1993 August 20. Emission lines are labeled.

Astrometry provided by the GASP³ program was used to determine accurate coordinates for at least six bright stars in each of our fields. We then performed a least squares fit to transform from the rectangular coordinate system of our CCD data to equatorial coordinates. Coordinates for the ob-

jects are listed in Table 1. Positions given are accurate to better than $0.1''$ in right ascension and 1 arcsec in declination.

2.3 Spectroscopy of the *BRI* Quasars

Follow-up spectroscopy was performed at the ESO NTT using the EMMI spectrograph. Low resolution (3.00 Å/pixel , 12.0 Å resolution) spectra of BRI 1500+08 (2700 s) and BRI 2235-03 (two 3600 s exposures) obtained on the nights

³Guide Stars Selection System Astrometric Support Program developed at the Space Telescope Science Institute (STScI is operated by the Association of Universities for Research in Astronomy, Inc. for NASA).

TABLE 2. Emission line redshifts and observed equivalent widths.

QSO	Line	λ_{obs} (Å)	z	Eq W (Å)
BRI 0103+00	Ly α	6605	4.433 ± 0.005	385 ± 15
	O I + Si II	7097	4.434 ± 0.005	18 ± 1
	C IV	8415	4.432 ± 0.005	179 ± 3
	Adopted redshift =		4.433 ± 0.005	
BRI 0151-00	Ly α	6323	4.201 ± 0.005	360 ± 10
	O I + Si II	6779	4.191 ± 0.005	23 ± 5
	Si IV + O IV	7286	4.197 ± 0.005	30 ± 4
	C IV	8049	4.196 ± 0.005	175 ± 15
	C III]	9906	4.189 ± 0.005	66 ± 15
	Adopted redshift =		4.196 ± 0.005	
BRI 1500+08	Ly α	6023	3.95 ± 0.02	103 ± 10
	Si IV + O IV	6965	3.97 ± 0.02	—
	C IV	7676	3.96 ± 0.02	—
	Adopted redshift =		3.96 ± 0.02	
BRI 2235-03	Ly Limit	4770	4.23 ± 0.02	—
	Ly α	6370	4.24 ± 0.02	81 ± 8
	Si IV + O IV	7325	4.23 ± 0.02	18 ± 3
	C IV	8093	4.22 ± 0.02	11 ± 2
	Adopted redshift =		4.23 ± 0.02	
QSO 0111-2838	Ly α	6174	4.079 ± 0.005	209 ± 8
	Si IV + O IV	7070	4.042 ± 0.005	39 ± 3
	C IV	7810	4.042 ± 0.005	98 ± 6
	C III]	9673	4.067 ± 0.010	94 ± 8
	Adopted redshift =		4.042 ± 0.005	

of UT 1993 August 19 and 20 were flux calibrated using a standard star from Hamuy *et al.* (1992), Baldwin & Stone (1984) and Stone & Baldwin (1984). Wavelength calibration, using a polynomial fit to helium and argon arcs, has residuals of ~ 0.3 Å. We also obtained spectra of two candidates from the BRI 0111-28 field at this time which were identified as red stars. Low resolution (3.65 Å/pixel, 14.6 Å resolution) spectroscopy was obtained on UT 1993 December 8-10 at the ESO NTT on the objects BRI 0103+00 (1500 s) and BRI 0151-00 (1200 s). A 1500 s spectrum of a third candidate from the BRI 0111-28 field was also obtained at this time, identifying this object as a quasar. However, this object cannot be identified as BRI 0111-28 due to its sufficiently different redshift from that quoted by Irwin & McMahon (1990). It is also about one magnitude below the limit of the Irwin *et al.* survey, an unusually large amount to be attributed to variability. The spectra were flux calibrated using a standard star from Baldwin & Stone (1984). Wavelength calibration, using a polynomial fit to helium and argon arcs, has residuals of ~ 0.3 Å.

Low resolution spectra of the four BRI quasars are shown in Fig. 3 with emission line redshifts and observed equivalent widths given in Table 2. Because all of the spectra were obtained in marginally nonphotometric weather, the flux zero

points have been adjusted to be consistent with the aperture photometry.

As a measurement of the discontinuity across the Ly α line, we have computed the continuum depression, parametrized by Oke & Korycanski (1982) as

$$D_A = \langle 1 - [f_\nu(\text{observed})/f_\nu(\text{continuum})] \rangle,$$

for each spectrum as outlined by Schneider *et al.* (1989). D_A is measured between rest wavelengths of 1050 and 1170 Å. Where the spectrum did not extend far enough to the blue, D_A was computed between our blue limit and 1170 Å. A power law was assumed to estimate the continuum flux. The value of D_A for each spectrum is listed in Table 1.

For BRI 0103+00 we derive an emission-line redshift of 4.433 ± 0.005 based on the O I + Si II and C IV lines [Fig. 3(a)]. The Si IV + O IV lines are obscured by atmospheric absorption. We detect the presence of a C IV absorption doublet at $z = 3.32$ (6690 and 6702 Å).

For BRI 0151-00 we derive an emission-line redshift of 4.196 ± 0.005 [Fig. 3(b)] based on the C IV and Si IV + O IV lines. We detect the presence of Ly α absorption at 6282 Å, N V at and 6426 Å, and C IV at 7999 and 8013 Å [denoted by vertical bars in Fig. 3(b) which we identify as an absorption system at $z = 4.17$].

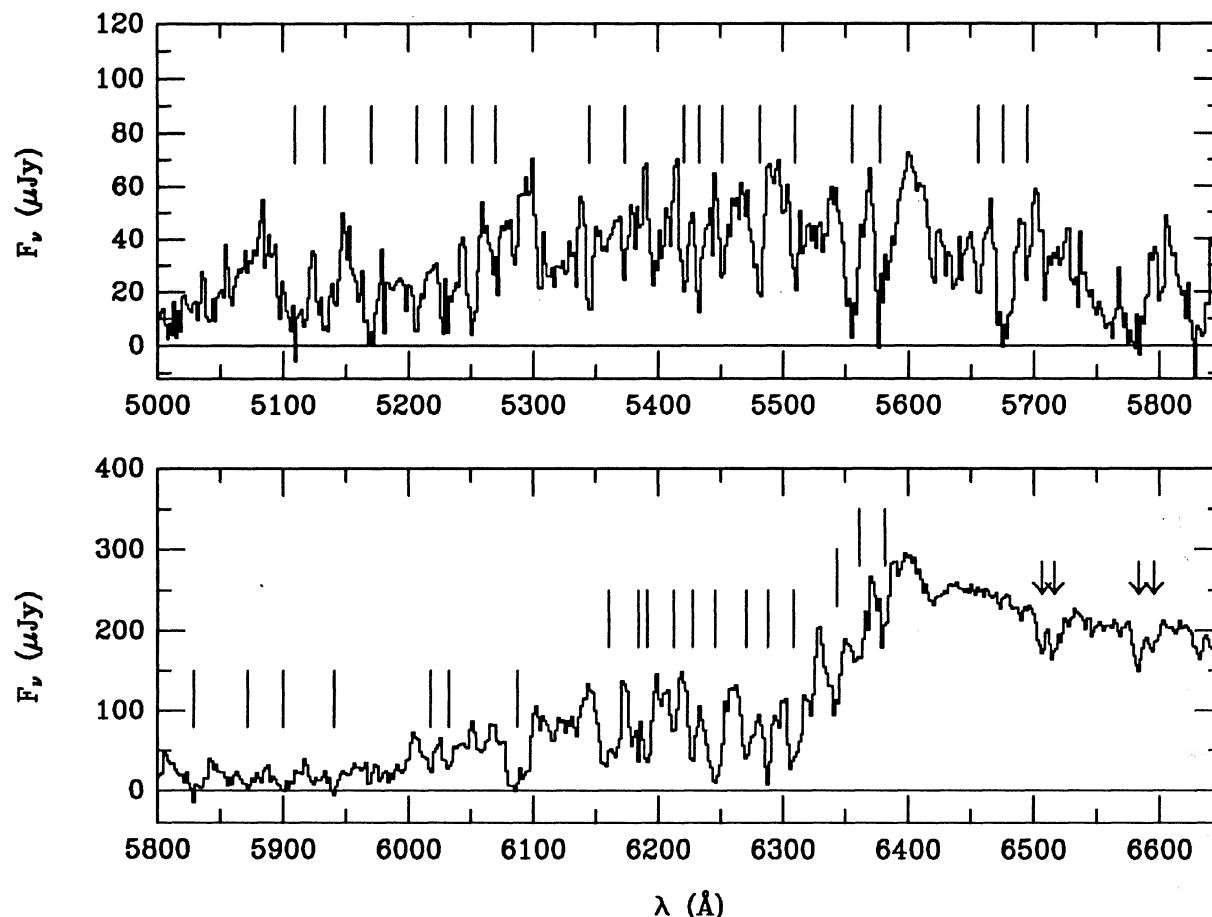


FIG. 4. Moderate resolution spectrum of the quasar BRI 2235-03 taken with the EMMI spectrograph at the ESO NTT. The vertical lines mark detected Ly α absorption features. The arrows indicate two sets of C IV doublets.

The spectrum of BRI 1500+08 [Fig. 3(c)] has been Gaussian smoothed with $\sigma=2$ pixels. We derive an emission-line redshift of 3.96 ± 0.02 based on the C IV and Si IV+O IV lines. The C IV and Si IV+O IV lines are heavily affected by atmospheric absorption, making the redshift less certain. We detect an absorption system at 8140 and 8159 Å which we identify as Mg II absorption at $z=1.91$. This identification is made more certain by the presence of Fe II absorption at 7565, 6935, and 6822 Å (rest wavelengths of 2600, 2383, and 2344 Å, respectively).

2.4 Follow-up Observations of BRI 2235-03

Two 3600 s low resolution spectra of BRI 2235-03 were obtained at the ESO NTT under variable conditions and coadded [Fig. 3(d)]. After applying the r band photometry to adjust the flux zero points of the spectrum, we find $R=18.6 \pm 0.2$. The estimated detection limit for the B band data is $20^m.5$. The estimated B magnitude for the quasar is ≈ 21.5 , which is well below this limit. Therefore, we regard the $(B-R)$ color calculated by DAOPHOT to be a lower limit as denoted by the arrow in Fig. 1. We derive an emission-line redshift for the quasar of 4.24 ± 0.02 based on the Si IV+O IV and C IV lines (Table 2). This object shows features typical

of BAL quasars. Notice the broad absorption feature at ~ 6700 Å, probably due to Si IV+O IV absorption and the absorption at ~ 7450 and ~ 7800 Å probably due to C IV. The value of D_A given in Table 1 for this object is very uncertain because the continuum is difficult to define.

Moderate resolution spectroscopy was obtained for BRI 2235-03 on the night of UT 1993 August 21 in nonphotometric weather at the ESO NTT with the EMMI spectrograph. In the blue (4300–6800 Å) a grism with a dispersion of 1.8 Å/pixel (7 Å resolution) was used while in the red (6200–8500 Å) a different grism gave 1.6 Å/pixel (6.2 Å resolution). Wavelength calibration, using a polynomial fit to helium and argon arcs, has residuals of ~ 0.2 Å (blue) and ~ 0.8 Å (red). The two spectra were combined after extraction by coaveraging overlapping regions. Numerous Ly α forest lines are detected in this spectrum (Fig. 4, Table 3). Two absorption systems are also readily detected by the presence of C IV doublets at ~ 6511 Å ($z=3.20$) and 6588 Å ($z=3.25$) (denoted by arrows in Fig. 4) with corresponding Ly α absorption at 5109 and 5170 Å.

Deep R and I band imaging was obtained on UT 1993 August 21 with EMMI with a scale of 0.347 arcsec/pixel [Fig. 5(a)]. A model point spread function (PSF) was con-

TABLE 3. Detected Ly α forest lines for BRI 2235–03 Å.

5109.4	5133.3	5170.3	5206.7
5230.0	5251.2	5269.7	5345.0
5373.5	5420.8	5432.8	5451.6
5481.5	5510.1	5555.2	5577.4
5656.1	5676.0	5695.3	5828.9
5871.6	5900.0	5940.8	6017.8
6032.1	6087.0	6160.2	6183.8
6190.8	6212.0	6227.5	6245.3
6270.6	6287.7	6308.8	6343.7
6361.5	6381.9		

structed from several stars in the field and used to subtract the quasar from the image, revealing a faint ($\sim 23^m$) galaxy 1.8 arcsec south of the quasar [Fig. 5(b)]. In the low resolution spectra of BRI 2235–03, the slit was oriented north–south, catching this galaxy as well. The spectrum of this object shows no obvious emission, but it has detectable continuum emission blueward of where the Ly limit (912 Å) would be if the object were at the redshift of BRI 2235–03. Therefore it is unlikely that this object is at the same redshift as the quasar and it must be a foreground galaxy. It is possible that this galaxy is responsible for one of the absorption systems seen in the spectra of the quasar.

The spectrum of BRI 2235–03 has a continuum that rises sharply to the red [Fig. 3(d)]. This prompted us to obtain infrared imaging of this field. This imaging was performed at the Palomar 200 in. telescope on the night of UT 1993 November 24 giving $J=16.73 \pm 0.05$, $H=16.00 \pm 0.07$, and $K=15.33 \pm 0.05$. These magnitudes as well as R and I magnitudes are plotted in Fig. 6 in terms of the specific power, computed as $P_{\nu_0} = 4\pi D_L^2 f_{\nu_0}$, and the specific luminosity, $\nu_0 P_{\nu_0}$, versus ν_0 (emitted frequency). D_L is the luminosity

distance. We have assumed $H_0=75$ km/s/Mpc and $q_0=0.1$ throughout.

As a comparison, PC 1247+3406, the most distant quasar known, and Q0051–279 are also plotted in Fig. 6. Infrared magnitudes of PC 1247+3406 obtained on UT 1992 March 18 at the Palomar 200 in. telescope were found to be $J=18.5 \pm 0.1$, $H=17.9 \pm 0.1$, and $K=17.2 \pm 0.1$. Optical data for PC 1247+3406 can be found in Schneider *et al.* (1991b). For Q0051–279, infrared data were taken from Carico *et al.* (1988) and optical data from Warren *et al.* (1987). The slope of the infrared region of the BRI 2235–03 data is comparable to that of the other two quasars presented. However, the BRI 2235–03 spectrum rises sharply from the optical to the infrared, making it a very red object.

At the redshift of BRI 2235–03, the K band is roughly equivalent to the rest frame B band. Therefore L_{bol} can be computed as $L_{\text{bol}} = 16 \nu_0 P_{\nu_0}$ (Chokshi & Turner 1992). For BRI 2235–03, we find $L_{\text{bol}} = 1.0 \times 10^{49}$ ergs/s $= 2.6 \times 10^{15} L_{\odot}$, assuming a cosmology of $H_0=75$ km/s/Mpc and $q_0=0.1$. This makes it one of the most luminous objects known, comparable to IRAS F10214+4724 (Rowan-Robinson *et al.* 1993), HS 1946+7658 (Hagen *et al.* 1992), Q0000–26 (Webb *et al.* 1988).

3. A NEW $z > 4$ QUASAR, QSO 0111–2838

The 1500 s spectrum of our third color-selected candidate in the field of BRI 0111–28 is shown in Fig. 7. This object was identified as a quasar with $z=4.042$. Irwin & McMahon (1990) list the redshift for BRI 0111–28 as 4.30, so we can only conclude that this object is a new quasar which we have designated as QSO 0111–2838. The object is a magnitude fainter in R than BRI 0111–28, with aperture photometry giving $R=19.75$. This object was undetected in B , which has an estimated detection limit of $23^m.5$, so the $(B-R)$ color is

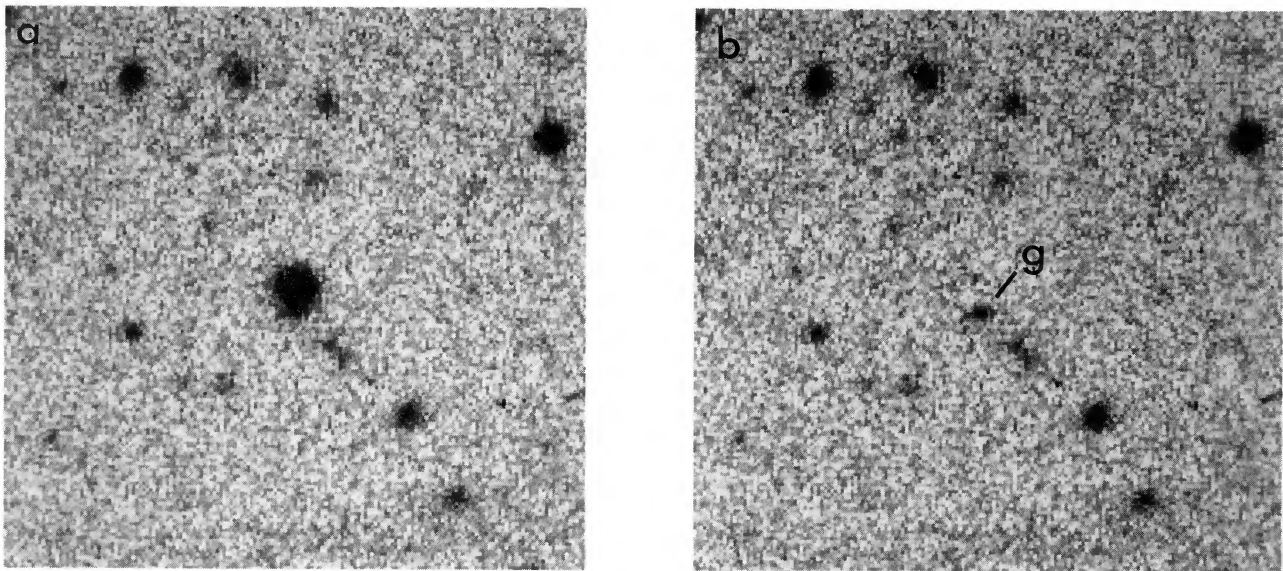


FIG. 5. (a) A 1080 s combined R and I image of BRI 2235–03 taken at the ESO NTT on UT 1993 August 20 and 21. (b) The same image with the quasar subtracted using a model PSF . Note the faint galaxy (designated “g”) directly south of the quasar. The images are 1 arcmin square with north up and east to the left.

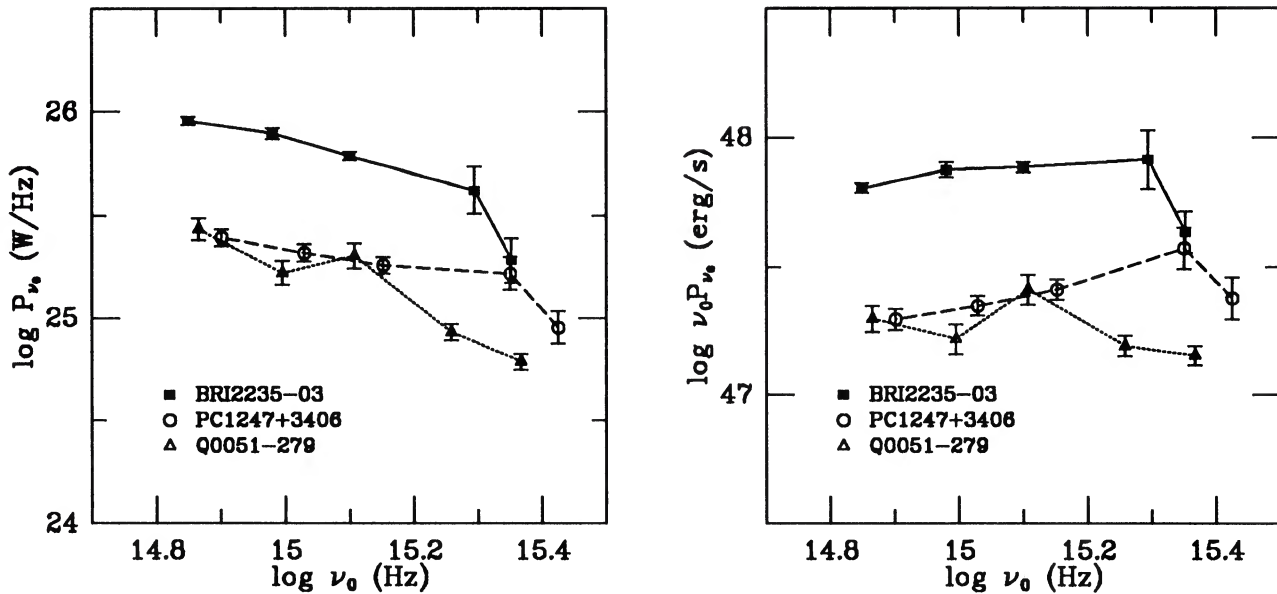


FIG. 6. Spectra of the three quasars BRI 2235-03 (filled squares), PC 1247+3406 (open circles), and Q0051-279 (open triangles) plotted in terms of the specific power, P_{ν_0} , and the specific luminosity, $\nu_0 P_{\nu_0}$, vs the emitted frequency, ν_0 .

a lower limit as indicated by the arrow in Fig. 1.

A 120 s i band image was obtained at the ESO NTT on the night of UT 1993 December 10 (Fig. 7). The quasar appears slightly extended. This suggests that the quasar is superposed with a foreground galaxy that may be acting as a gravitational lens, thereby magnifying the quasar. However, we need better imaging data before more can be said.

Because the spectrum (Fig. 8) was obtained in nonphotometric weather, the flux zero points have been adjusted to be consistent with the aperture photometry. We derive an emission-line redshift of 4.042 ± 0.005 based on the C IV and Si IV+O IV lines (Table 2). We detect Ly α absorption at

6036 Å, Si IV+O IV at 6962 Å and C IV at 7687 Å, as denoted by the vertical lines in Fig. 8, which we identify as an absorption system at $z=3.97$. We also detect the presence of a C IV absorption doublet at $z=3.12$ (6384 and 6394 Å). The coordinates, adopted redshift, R magnitude, and continuum depression value for this object are listed in Table 1.

The question remains as to why we failed to detect BRI 0111-28. It could have been overlooked due to some chip defect. More likely, it is lower down on our candidate list and we have been unable to obtain a spectrum to date.

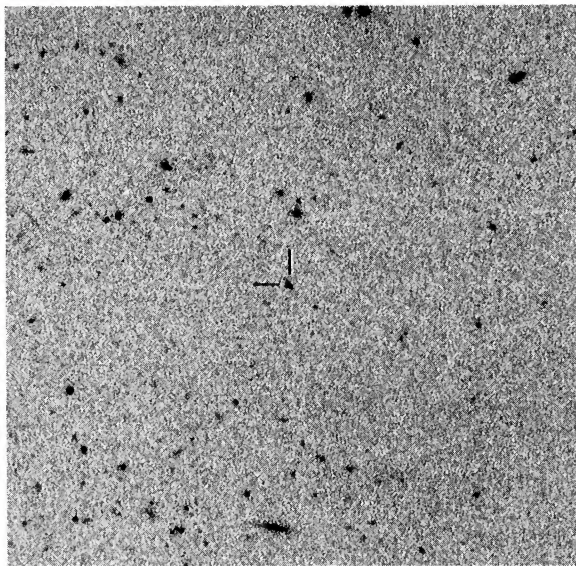


FIG. 7. A 120 s I band image of QSO 0111-2838 taken at the ESO NTT using EMMI. The image is 4 arcmin square with north up and east to the left.

4. CONCLUDING REMARKS

In the course of this survey, we have identified six *BRI* quasars, four of them reported here. One of them, BRI 2235-03, is one of the most luminous objects now known, with $L_{\text{bol}} = 1.0 \times 10^{49}$ ergs/s $= 2.6 \times 10^{15} L_{\odot}$. We have also discovered a new $z > 4$ quasar with $R=19.75$, almost a magnitude lower than the stated limit of the *BRI* survey. This further demonstrates the utility of wide-field CCD imaging in the search for high-redshift quasars in order to cover large areas of sky at magnitudes fainter than photographic multicolor surveys.

We have obtained multicolor data on several of these re-discovered *BRI* quasars for use in our protocluster search. We have several good candidates from these fields that await follow-up spectroscopy. We hope to obtain additional multicolor and narrowband imaging in the fields reported here. Reports on this work will be presented in future papers of this series.

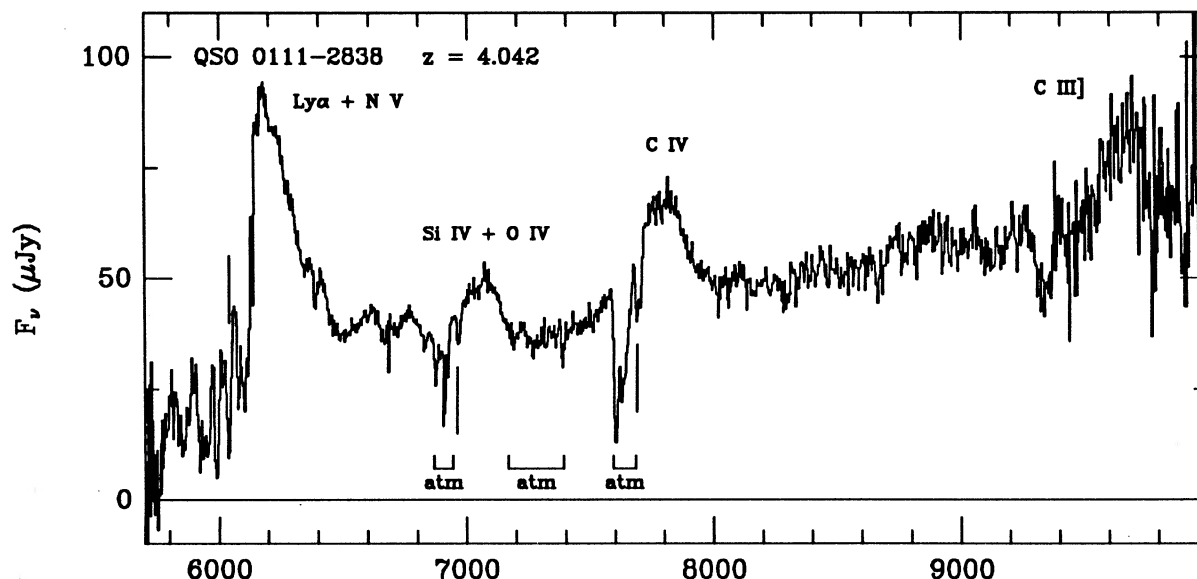


FIG. 8. An 1800 s low resolution spectrum of the previously unknown quasar QSO 0111-2838, $z=4.042$, taken with the EMMI spectrograph on the ESO NTT. Emission lines are labeled.

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