THE BTC40 SURVEY FOR QUASARS AT 4.8 < z < 6

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ABSTRACT

The BTC40 Survey for high-redshift quasars is a multicolor search using images obtained with the Big Throughput Camera (BTC) on the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope in V, I, and z filters to search for quasars at redshifts of 4.8 < z < 6. The survey covers 40 deg² in B, V, and I, and 36 deg² in z. Limiting magnitudes (3σ) reach to V = 24.6, I = 22.9, and z = 22.9. We used the V − I versus I − z two-color diagram to select high-redshift quasar candidates from the objects classified as point sources in the imaging data. Follow-up spectroscopy with the Anglo-Australian Telescope and CTIO 4 m telescopes of candidates having I ≤ 21.5 has yielded two quasars with redshifts of z = 4.6 and z = 4.8, as well as four emission-line galaxies with z ≈ 0.6. Fainter candidates have been identified down to I = 22 for future spectroscopy on 8 m class telescopes.

Key words: quasars: general — surveys

1. INTRODUCTION

Surveys for faint quasars at z > 4.5 and the subsequent constraints they place on the quasar luminosity function (QLF) will eventually determine how luminosity evolution and density evolution each contribute to the declining space density of quasars established for 3 ≤ z ≤ 4.3 (Warren, Hewett, & Osmer 1994, hereafter WHO; Schmidt, Schneider, & Gunn 1995, hereafter SSG; Kennefick, Djorgovski, & de Carvalho 1995) and now observed out to redshifts of z ≈ 5 (Fan et al. 2001b). The QLF in turn is an important input to models of structure formation in the early universe (Haehnelt, Natarajan, & Rees 1998).

Additionally, high-redshift quasars provide insight into the nature of quasars and their environments in the early universe (Haehnelt & Kauffmann 2000), contribute to the ionizing UV background (Madau, Haardt, & Rees 1999), and act as background illumination for absorption-line studies of the intergalactic medium. It is therefore important to continue to search for quasars of all luminosities at the highest possible redshifts, and thus the earliest possible epochs.

We began this survey to address the shape of the QLF at redshifts z ≥ 5. WHO found evidence that the positive evolution in the QLF at 0 < z < 2.2 continues to z ≈ 3.3, and then the space density declines by a factor of 6.5 at z = 4. SSG found that space densities have a maximum between z = 1.7 and 2.7 and then decrease by a factor of 2.7 per unit redshift beyond z = 2.7. Extrapolations of these QLFs to 5 < z < 6 predict 0.02 (WHO) to 0.6 (SSG) quasars per square degree to I = 22.

The major effort to find quasars at higher redshifts is the Sloan Digital Sky Survey (SDSS), which continues to be remarkably successful at finding z > 4 quasars. SDSS has discovered more than 100 such objects including one at z = 6.3, the most distant published (see, e.g., Fan et al. 2000, 2001c; Anderson et al. 2001). However, SDSS is limited to z > 4.5 quasars with MB ≲ −26 and misses the bulk of the population, which is found at lower luminosities. Thus there is a need for surveys to find less luminous z > 4.5 quasars to address the shape of the faint end of the QLF. Sharp et al. (2001) have presented initial results from one such survey, finding two z > 4.5 quasars to i ≈ 21.5 in 10 deg² of griz data.

The BTC40 survey is a deep, 40 deg² survey in BViz filters undertaken to search for clusters of galaxies, morphologically selected gravitational lenses, and quasars at z ≥ 4.8. The results on clusters and gravitational lenses will be presented elsewhere. In this paper we present results of our efforts using a 4 m telescope and large-format camera to complement the SDSS quasar search and extend it to lower luminosities.

We used the Viz imaging data to select quasar candidates over 36 deg² of sky, down to I ≤ 22, corresponding to absolute magnitudes of MB ≲ −24.7 at z = 4.8. The selection process compared the expected colors of quasars at redshifts 4.8 < z < 6 with the locations of cataloged stellar objects in V − I versus I − z color space. Follow-up spectroscopy at the Cerro Tololo Inter-American Observatory (CTIO) 4 m and Anglo-Australian Telescope (AAT) was attempted to I ≤ 21.5 and has resulted in the discovery of two quasars with redshifts of z = 4.6 and z = 4.8, as well as several emission-line galaxies at z ≈ 0.6. Spectroscopy of the fainter candidates, down to I = 22, will be the focus of our future efforts on larger telescopes.

We describe the survey imaging data in § 2, the candidate selection in § 3, and the follow-up spectroscopy in § 4. We discuss our results in § 5.
2. IMAGING

2.1. Observations

The Big Throughput Camera (Tyson et al. 1992; Wittman et al. 1998) contains a 2 × 2 array of thinned 2048 × 2048 SITE CCDs with 24 μm pixels. Used at the prime focus of the CTIO 4 m Blanco Telescope (since replaced by the MOSAIC camera), the BTC plate scale is 0′′.43 pixel⁻¹, resulting in a sky area of 14′.7 × 14′.7 imaged by each CCD. The CCDs are separated by 5′/4 for noncontiguous coverage of 0.24 deg² per pointing.

Six survey fields (Table 1) were selected with declinations to provide low air mass, and |b| chosen to minimize Galactic H I and contamination by stars. The survey was split between spring and fall data sets, each containing three fields separated by ~2.5 hr in right ascension.

Initial BTC imaging in the Johnson-Cousins B V I filters and Kron-Cousins I filters was performed at the Blanco 4 m telescope at CTIO in the spring and fall semesters of 1997 (Table 2). A “lawn-mowing” pattern was used, in which the telescope moved back and forth first in right ascension and then in declination. An overlap of 1′ in both directions provided continuity between adjacent pointings for later “bootstrapping” of the photometry.

The V and I data were reduced and catalogs produced (both procedures are described below for the full data set) and ≈200 objects with $V - I > 4.0$ were selected as candidates for $z > 5$ quasars. The B data were not used for the quasar survey because the $B - V$ color provides no useful information for finding high-redshift quasars; the 912 Å Lyman limit is well into the B filter by $z = 4.8$, while the flux in $V$ is heavily depressed by the Lyα forest. Spectroscopy was performed at the CTIO 4 m on 20 of the brighter candidates under poor conditions in 1998 April. All of these candidates turned out to be late-type (M5 or later) stars. In light of this result we resolved to improve the survey efficiency and reduce cool-star contamination of the quasar candidate sample by obtaining follow-up imaging in the near-infrared $z$ filter.

The $z$ filter in use at CTIO is a long-pass filter matching the response of the $z'$ filter in the SDSS (Fukugita et al. 1996; Gunn et al. 1998). The filter uses RG830 Schott color glass to provide the short-wavelength cutoff, and the long-wavelength response is determined entirely by the decreas-

### TABLE 1
BTC40 Fields

| Field | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | $\beta^1$ | $\beta^\prime$ | Area (deg²) |
|-------|------------------|------------------|------|------|--------------|
| F1    | 09 50 41         | 07 06 51         | 229.4428 | 42.7567 | 5.76         |
| F2    | 12 08 32         | −19 44 16        | 289.2985 | 41.9954 | 7.68         |
| F3    | 14 32 05         | 00 41 10         | 349.5323 | 54.1881 | 5.46         |
| F4    | 23 52 14         | −40 12 00        | 342.3103 | −72.0884 | 3.84         |
| F5    | 02 26 54         | 00 18 55         | 166.7328 | −54.2300 | 5.76         |
| F6    | 05 38 22         | −28 12 44        | 232.3380 | −27.4770 | 7.68         |

Note. — Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

a Area covered by the $V$, $I$, and $z$ filters.

### TABLE 2
Journal of CTIO Imaging Observations

| Field | Filter | UT Date     | Exp. Time | 5σ Limiting Magnitude | 3σ Limiting Magnitude |
|-------|--------|-------------|-----------|-----------------------|-----------------------|
| F1    | $V$    | 1997 Mar 14, 16–17 | 300 | 23.6 ± 0.2 | 24.2 ± 0.2 |
|       | $I$    | 1997 Mar 14, 16–17 | 150 | 22.2 ± 0.2 | 22.7 ± 0.2 |
|       | $z$    | 1999 Feb 21–22   | 300 | 22.2 ± 0.2 | 22.7 ± 0.2 |
| F2    | $V$    | 1997 Mar 14, 16–17 | 300 | 24.3 ± 0.1 | 24.8 ± 0.1 |
|       | $I$    | 1997 Mar 14, 16–17 | 150 | 22.7 ± 0.1 | 23.2 ± 0.1 |
|       | $z$    | 1999 Feb 21–22   | 300 | 22.6 ± 0.1 | 23.1 ± 0.1 |
| F3    | $V$    | 1997 Mar 14, 16–17 | 300 | 24.1 ± 0.2 | 24.6 ± 0.2 |
|       | $I$    | 1997 Mar 14, 16–17 | 150 | 22.4 ± 0.1 | 23.0 ± 0.1 |
|       | $z$    | 1999 Feb 21–22   | 300 | 22.5 ± 0.2 | 23.0 ± 0.2 |
| F4    | $V$    | 1997 Nov 26      | 300 | 24.0 ± 0.1 | 24.6 ± 0.1 |
|       | $I$    | 1997 Nov 26–27   | 150 | 22.2 ± 0.1 | 22.8 ± 0.1 |
|       | $z$    | 1998 Nov 24–25   | 300 | 22.3 ± 0.2 | 22.9 ± 0.2 |
| F5    | $V$    | 1997 Nov 24, 26–27 | 300 | 23.9 ± 0.2 | 24.4 ± 0.2 |
|       | $I$    | 1997 Nov 24, 26–27 | 150 | 22.2 ± 0.2 | 22.8 ± 0.2 |
|       | $z$    | 1998 Nov 25–27   | 300 | 22.2 ± 0.1 | 22.8 ± 0.1 |
| F6    | $V$    | 1997 Nov 24, 26–27 | 300 | 24.1 ± 0.1 | 24.7 ± 0.1 |
|       | $I$    | 1997 Nov 24, 26–27 | 150 | 22.4 ± 0.2 | 22.9 ± 0.2 |
|       | $z$    | 1998 Nov 24–25   | 300 | 22.4 ± 0.2 | 22.9 ± 0.2 |

* Exposure time per pointing within a field.
We processed the reduced images with the SKICAT software package (Weir et al. 1995) to generate our object catalogs. Briefly, SKICAT uses FOCAS (Jarvis & Tyson 1981; Valdes 1982) for object detection, photometry, and object classification. The resulting catalogs reside in an online SYBASE database and are easily accessed through the SKICAT interface. Queries can be performed on the database to, e.g., select point sources within a given magnitude range. Our database contains approximately 476,000 stellar objects with $I \geq 16$ down to the $3\sigma$ limits ($V = 24.6$, $I = 22.9$, $z = 22.9$) of the survey.

An important component of SKICAT is the ability to match features between catalogs based on their measured positions. For this survey our objective was to construct matched $VIz$ catalogs of objects classified as point sources in the $I$ filter and use them to create $V-I$ versus $I-z$ two-color diagrams of the survey area, as described in § 3. Construction of the matched catalogs relies on the object coordinates; therefore the astrometry of the objects must be accurate.

2.4. Astrometry

The large field of view of the BTC results in images with significant geometric distortions due to sky curvature, slight rotations between the chips, and distortions of the prime focus corrector (Wittman et al. 1998). Therefore accurate astrometry of objects cataloged in this survey had to be established before matching could be performed between filters. We used the UNDIST ray-tracing program (written by I. Dell'Antonio) in a two-step process to correct the positions contained in the object catalogs. For a given pointing (including R.A., decl., hour angle, and filter) the program generates a grid of CCD $x$, $y$ pairs with corresponding right ascension and declination, based on the known optical properties of the BTC and several input parameters (field center, hour angle, filter, and date of observing run). The IRAF tasks GEOMAP and GEOXYTRAN use the output spatial information to compute and perform the transformation from the FOCAS $x$, $y$ coordinates of cataloged objects into right ascension and declination values.

A first run through this process produced an initial correction to the object coordinates. We then downloaded USNO catalogs (Monet et al. 1998) of the stars in the areas of the sky covered by each pointing and compared the coordinates of stars common with the USNO and survey catalogs to produce a set of offsets ranging from a few arcseconds up to $\sim 2''$ for some fields. We used these as the input to a second pass of the IRAF routines to refine the transformation and, from this result, calculated new object coordinates and updated the database. The rms residuals on the fit to the USNO coordinates were on the order of $\approx 0.4''$.

2.5. Photometry

Conditions during the imaging runs were generally not photometric. To calibrate the data, we determined initial rough zero points for the data from standard stars observed at the beginning and end of each night. In an initial test of the candidate selection criteria (§ 3) the position of the stellar locus in color-color space fluctuated from field to field, indicating changing conditions over the course of the run and the individual nights. Portions of some nights may have been photometric, but standard-star observations obtained

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8 CCDs 1 and 2 of the BTC were replaced in 1998 May, between the $BV$ and the $z$ runs.
9 IRAF is distributed by the NOAO, which is operated by the AURA, under cooperative agreement with the NSF.
10 Part of Pat Hall’s Add-on Tasks (PHAT) under IRAF.
under photometric conditions were not extensive enough to allow a precise photometric solution for the full data set. However, note that, when selecting high-redshift quasar candidates, only accurate differential photometry is crucial. Candidates are chosen by where they lie with respect to the stellar locus in color-color space, making absolute photometry less critical.

Nevertheless, we took several steps to ensure the accuracy of the absolute photometry. We created a model stellar locus using the Bruzual-Persson-Gunn-Stryker (BPGS) spectrophotometric atlas available in the STSDAS/SYNPHOT package under IRAF. This atlas is an extension of the Gunn-Stryker optical atlas (Gunn & Stryker 1983) into the UV and also includes infrared data from Strecker, Erickson, & Whittenborn (1979). The stellar locus results from folding the colors through the combined CCD/filter response and plotting the resulting $V-I$ versus $I-z$ colors. After creating and examining color-color plots of $V-I$ versus $I-z$ for individual pointings, we selected a pointing from the spring data set as having been taken under near optimal conditions based on the tightness of the observed stellar locus and its overlap of the model stellar locus. We determined the shifts in color-color space needed to put each pointing onto the same scale by using a light table and evaluating the necessary shifts by eye. We eliminated four pointings of field 6 from candidate selection based on the low numbers of objects and the degree of scatter in the resulting stellar locus. Visual inspection of these fields and the observing logs indicate conditions were especially poor at the time of these observations.

One of the survey fields was originally chosen to overlap part of the faint photometric calibration sequence of Boyle et al. (1995). We compared our final photometry of the sources in this $6' \times 6'$ overlap region with the values from the catalogs of field 866 in Boyle et al. The result is shown in Figure 2. The magnitudes agree well for $I < 19$, neglecting the two brightest objects, which are saturated in the BTC40 data. At the fainter end, however, the figure suggests a discrepancy of several tenths of a magnitude between the two measurements. We intend future observations of the survey fields to refine the survey photometry, but, as noted above, the relative photometry was adequate for selecting high-redshift quasar candidates.

The journal of observations in Table 2 includes the average 3 and 5 $\sigma$ magnitude limits reached in each survey field. The average limiting magnitudes (5 $\sigma$) for the imaging data over the entire survey are $V = 24.0, I = 22.4$, and $z = 22.4$ (AB95). Note that the original BTC CCD chip No. 1 was less sensitive than the other three, especially in the blue (Wittman et al 1998). As a result, the 5 $\sigma$ limiting magnitudes for chip No. 1 in $V$ are $\Delta m_{\lim, V} \approx 0.1–0.3$ brighter than those of chips Nos. 2, 3, and 4. The chip No. 1 sensitivity in the $I$ filter was less discrepant, keeping any effect on the limiting magnitude $\Delta m_{\lim, I} \leq 0.1$ for chip No. 1 data. Because the $V$ data are much deeper than the $I$ data, and candidate selection was limited to $I \leq 21.5$ variations in chip sensitivity ultimately did not influence candidate selection.

### 3. Candidate Selection

The general region of $V-I$ versus $I-z$ color space in which $4 < z < 6$ quasars will be found is readily seen in Figure 3, a plot of the stellar sequence taken from the BPGS stellar atlas in the STSDAS/SYNPHOT package. The quasar colors are from synthetic quasar spectra as described in Kennefick, Djorgovski, & Meylan (1996). We used this predicted region as a guide to selecting initial candidates from $V-I$ versus $I-z$ diagrams of BTC40 objects classified as point sources (FOCAS “stars” or “fuzzy stars”) in the $I$-band data. We performed a visual inspection of the images of those candidates to ensure the colors had not been skewed by cosmic-ray hits or cosmic flaws in the CCDs. Finally, a priority was assigned to each candidate, based on the magnitude, location in color-color space, and the visual inspection.

The selection process for our initial spectroscopy runs used magnitudes as calculated in SKICAT using FOCUS as described by Weir et al. (1995). FOCUS calculates two magnitudes: an aperture magnitude calculated within a specified

![Figure 2](https://example.com/figure2.png)  
**Figure 2.** Comparison of the $I$ magnitudes of stellar objects common to the BTC40 survey and field 866 of Boyle et al. (1995). The two brightest objects in the lower left-hand corner are saturated in the BTC40 data.

![Figure 3](https://example.com/figure3.png)  
**Figure 3.** Plot of $V-I$ vs. $I-z$ colors, showing the expected location of high-redshift quasars in color-color space (below and to the right of the solid selection lines). The dashed track follows the expected colors of quasars at redshifts from 4 to 6, with the colors of several redshifts marked. These colors were computed from 10 synthetic quasar spectra of varying continuum slopes and realizations of the Ly $\alpha$ forest in 0.1 redshift bins. At quasar redshifts of $z \sim 5$ quasars become progressively bluer in $I-z$ than the late-type stars of similar $V-I$, which enables the separation of the quasars from the stars in color-color space. The model stellar locus was calculated from the Bruzual-Persson-Gunn-Stryker spectrophotometric stellar database.
radius (we used 3 pixels during SKICAT processing) and a "total" magnitude based on an area of twice the detection area. As discussed by Weir et al. (1995), the total magnitude carries the associated risk of increased random error. After our first observing run in 1999 November at CTIO, in which only one observed candidate turned out to be a quasar, we compared the FOCAS photometry with magnitudes measured independently with PHOT in IRAF. We concluded that, for faint point sources, the random errors in the SKICAT/FOCAS measurement can be significant, moving stars out of the stellar locus and into the region of quasar candidate selection (and presumably vice versa).

Therefore we remeasured the magnitudes using the IRAF PHOT package and an aperture radius of 2 pixels (roughly twice the seeing) and proceeded to compile candidate lists based on the colors resulting from the IRAF photometry. Objects that were also in the selection area using FOCAS colors were given higher priority for follow-up spectroscopy. The initial spectroscopy runs allowed us to refine the selection criteria and estimate how close to the stellar locus we could reasonably hope to go. This determination requires balancing the number of candidates selected with the increasing likelihood of contamination by the cool stellar population as one moves closer to the stellar locus. Figure 4 shows the stellar locus from a portion of the survey data overplotted with the complete candidate set broken down by magnitude range. The objects in the region below and to the right of the lines satisfy the criteria used in selecting candidates.

![Fig. 4.—$V-I$ vs. $I-z$ plots of stellar objects in 4.75 deg$^2$ (field 3) of the survey, overplotted with triangles to indicate the objects selected as high-redshift quasar candidates. Filled triangles represent candidates we observed spectroscopically. The two quasars discovered are the open stars indicated by arrows in the top panel. The CNELGs are the three filled triangles with $V-I \approx 1.7$ in the top and middle panels. Typical errors on the photometry are plotted for $I-z = 0.2$ and $V-I = 3.0$. Dots appearing in the selection areas are due to bad CCD columns or cosmic rays and were eliminated by visual inspection of the $V$Iz images during the candidate-selection process.](image)

4. SPECTROSCOPY

We performed follow-up spectroscopy of selected candidates during three observing runs at the CTIO 4 m and three at the AAT (Table 3). Over the course of these six runs we were able to observe 82 quasar candidates. However, many of these are not included in our later survey sample of sixty-two candidates with $I \leq 21.5$, because of (1) the adoption of IRAF photometry after the first observing run and (2) modifications to the selection criteria based on results of the initial runs. We observed 40 objects from the list of 62 candidates, 27 at CTIO and 13 at the AAT; several promising candidates with inconclusive initial spectra were observed at both telescopes. In this section we describe the setup at the two locations and the data reduction process.

4.1. CTIO

We used the RC spectrograph at the CTIO 4 m with similar setups on 1999 November 14–16, 2000 May 9–11, and 2000 October 16–17. The RC spectrograph on the CTIO 4 m uses the Blue Air Schmidt (BAS) camera and a Loral 3K CCD, which we formatted to $3071 \times 800$ for faster readout. We chose the G181 grating (316 lines mm$^{-1}$) and the GG495 blocking filter for a resolution of 2 A˚ pixel$^{-1}$ over the range $\approx 5000–11000$ A˚. During good seeing conditions we maintained the slit width at 1" and opened it to 1.5" when the seeing deteriorated. Exposure times ranged from 900 to 3600 s, depending on the brightness of the candidate. We observed 27 candidates from our sample over the course of the three runs, down to a cutoff magnitude of $I \approx 21.5$.

4.2. AAT

We performed the spectroscopy at the AAT using LDSS++ with the 165 A˚ mm$^{-1}$ grating for a dispersion of 2.6 A˚ pixel, providing coverage over $\sim 5200–10000$ A˚. We used a long slit, 1" wide when possible, but in general we were limited by unfavorable conditions to a slit width of 1.7. LDSS++ can be operated in "nod and shuffle" mode (Glazebrook & Bland-Hawthorn 2001), in which the telescope is nodded rapidly by $10^\prime$–$20^\prime$, while the spectra are recorded on two adjacent regions of the MIT Lincoln Lab (MITLL) CCD through charge shuffling. The method allows optimal sky subtraction and is ideal for extracting fainter targets. Conditions were fair to poor for most of three observing runs, and we observed 13 candidates from our survey list.

4.3. Data Reduction

We reduced the candidate spectra with CCDRED under IRAF, including subtracting the overscan region and flat-fielding the data using quartz flats obtained during the runs.

**TABLE 3**

| Telescope | Instrument | UT Date |
|-----------|------------|---------|
| CTIO 4 m... | RC Spec. | 1999 Nov 14–16 |
| AAT 4 m...... | LDSS | 1999 Dec 2–6 |
| AAT 4 m...... | LDSS | 2000 Apr 2–4 |
| CTIO 4 m...... | RC Spec. | 2000 May 9–11 |
| AAT 4 m...... | LDSS | 2000 Aug 29–31 |
| CTIO 4 m...... | RC Spec. | 2000 Oct 16–17 |
For the nod-and-shuffle AAT data we performed the additional step of subtracting the two exposed regions of the CCD, effectively eliminating the night sky emission lines. We used the IRAF APALL task to select and size the apertures interactively and trace the spectra across the chip. We also specified the regions used for background subtraction in the CTIO data. We extracted arc calibration spectra by using traces obtained from standard-star spectra, used the IDENTIFY task on the arc spectra to obtain a dispersion solution, and proceeded to apply this solution to the extracted spectra of the candidates. Finally, we combined spectra of objects having multiple exposures. We also used extracted standard-star spectra to get the shape of the object spectra and a rough flux calibration.

### 4.4. Spectroscopic Results

The positions, $I$ magnitudes, colors, and, where possible, identifications of the observed candidates are given in Table 4. The list includes two quasars, 10 stars, three compact narrow emission-line galaxies (CNELGs), 15 objects that could not be identified due to the low signal-to-noise ratio of the spectra, and nine objects with spectra too faint to be extracted (but possessing no obvious emission lines).

#### 4.4.1. Quasars

Two of the identified objects are quasars at redshifts $z \geq 4.6$ and $z \approx 4.8$ and magnitudes of $I = 19.4$, toward the brighter limit of our survey. Finding charts for these quasars are given in Figure 5, and the spectra are presented in Figure 6. Both quasars show strong Ly$\alpha/N$ v emission and weaker emission due to C iv. Continuum flux shortward of Ly$\alpha$ is depressed by the intervening Ly$\alpha$ forest.

One of the quasars, BTC40 J2340–3949, was detected in the deep, 1.4 GHz ATESP radio survey (Prandoni et al. 2000), with a peak flux of 0.57 mJy. We can adapt the radio-optical flux ratio, $R_{\lambda_{opt}}$ of Kellerman et al. (1989) for a high-redshift source, substituting the $I$-band (8000 Å) magnitude for the $B$-band (4400 Å) and scaling

### Table 4

| No. | Name          | $\alpha$ (2000.0) | $\delta$ (2000.0) | $I$     | $V-I$ | $I-z$ | Notes          |
|-----|---------------|------------------|------------------|--------|------|------|----------------|
| 15   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 16   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 17   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 18   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 19   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 20   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 21   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 22   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 23   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 24   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 25   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 26   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 27   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 28   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 29   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 30   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 31   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 32   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |
| 33   | BTC40 J0046–0046 | 00 46 02.6       | −21 24 36.7      | 19.15  | 2.30 | 0.15 | M star         |

* An emission-line galaxy at $z = 0.58$ lies $36^\circ$ north of the candidate.
the radio flux to the proportionally lower frequency $\nu(8000/4400)^{-1}$ by assuming a power law of the form $f \sim \nu^{-0.5}$. In this case, $R_{\nu_0} \approx 10$, putting the quasar just on the border of being classified as radio-loud. BTC40 J2340–3949 may have a weak BAL trough (or strong associated absorption) seen in N v at $\lambda \approx 6945$ Å and C iv at $\lambda \approx 8680$ Å (the absorption at 7600 Å is atmospheric) and may therefore be similar to the radio-moderate BAL quasars discovered in large numbers by the FIRST Bright Quasar Survey (Becker et al. 2000).

4.4.2. Compact Narrow Emission-Line Galaxies

We report the discovery of three compact narrow emission-line galaxies (CNELGs) with $0.55 < z < 0.6$. The positions, I magnitudes, and colors are provided for the CNELGs in Table 4, finding charts are given in Figure 7, and the spectra are shown in Figure 8. The galaxies exhibit point-source profiles and [O iii] $\lambda\lambda 4959, 5007$ emission shifted into the I filter at $z \approx 0.6$, giving them colors similar to our quasar candidates. All three galaxies have $V-I \approx 1.7$, making them, along with the quasar BTC40 J2340+0119 ($V-I = 1.71$), the bluest $V-I$ candidates in the sample, and the spectra show [O iii] $\lambda\lambda 4372$ and probable [Ne iii] $\lambda 3869$, as well as H$\beta$ in one case.

BTC J0949+0715 is almost certainly a Seyfert 2 galaxy, based on the emission-line diagnostics of Baldwin, Phillips, & Terlevich (1981) and Rola, Terlevich, & Terlevich (1997). Even though H$\beta$ is detected in this object, it is very weak relative to [O iii] $\lambda 5007$, and such a ratio is a good sign of AGN activity.

The other galaxies appear to be starburst galaxies, though within the fairly large uncertainties, BTC J1430+0107 could be an AGN as well.

Finally, we note the serendipitous discovery of a galaxy at $z = 0.58$, as measured from narrow O iii, O ii, and H$\beta$ emission lines seen in the spectrum (Fig. 8, bottom). The galaxy is too faint for its morphology to be established from the BTC image, but it lies $36''$ due north of quasar candidate BTC40 J2345–3948. Since the slit was oriented north-south, spectra for the candidate and galaxy were obtained simultaneously.

5. DISCUSSION

In our high-redshift quasar survey we have found two $I < 21.5$ quasars with $z = 4.6$ and $z = 4.8$ in 36 deg$^2$, prov-
ing the validity of the selection technique. Although our candidate selection is designed to be most sensitive for $z \geq 4.8$, when the Ly$\alpha$ emission line has moved into the $I$ filter, slightly lower redshift “Lyman-break” quasars may also enter the sample. This was the case with BTC 2340–3949.

To compare our results with SDSS, Anderson et al. (2001) found 29 quasars with $z \geq 4.5$ in $\approx 700$ deg$^2$ of the SDSS commissioning data, for a surface density of one quasar per 24 deg$^2$ to $i^* \leq 20.5$. Four of these quasars had $z > 5$, or one per 175 deg$^2$. In the fall equatorial stripe of the SDSS commissioning data Fan et al. (2001a) found five quasars with $4.5 \leq z \leq 4.77$ to $i^* \leq 20$ in 182 deg$^2$, or one in 36 deg$^2$. Thus our findings from the BTC40 survey are consistent with the early SDSS results, although the BTC40 statistical base is admittedly very small.

More formally, the expected number of quasars predicted by a given survey may be computed by numerically integrating the QLF determined by the survey over the redshift and magnitude ranges of interest and multiplying by the efficiency of the survey. Although we have not found enough quasars to derive a luminosity function, our results can be compared with predictions based on the QLF determined by the SDSS team.

Fan et al. (2001b) used the 39 quasars from the SDSS commissioning data to derive a QLF over the range $3.6 < z < 5$ and $-27.5 < M_{1450} < -25.5$, where $M_{1450}$ is the absolute continuum magnitude measured at $\lambda = 1450(1 + z)$ Å and calculated in the AB system. Since our quasar spectra are not spectrophotometric, we scaled them to return the $I$ magnitudes previously measured from the imaging data and then determined AB[$1450(1 + z)$]. Assuming the continuum follows a power law with slope $\alpha = -0.5$, then $M_{1450} = -26.6$ for BTC40 J2340–3949 and $M_{1450} = -26.8$ for BTC40 J1429+0119, and both quasars occupy the parameter space probed by SDSS.

When integrated over $4.5 < z < 5$, the luminosity function of Fan et al. (2001b) predicts a surface density of $\approx 0.026$ quasars deg$^{-2}$ down to $I \approx 20.3$, or $I = 19.89$ using the conversion between the AB and conventional magnitude systems from Fukugita et al. (1996). In the 36 deg$^2$ of the BTC40 survey, therefore, we would expect to find $\approx 1$ quasar with redshift $4.5 < z < 5$ and $I < 19.9$, and in fact the two quasars we found fall into this category. Furthermore, the absence of $z > 5$ quasars in our sample to date is understandable, given their scarcity in the SDSS fields. The SDSS luminosity function predicts 0.015 quasars deg$^{-2}$ with $5 < z < 6$ to $I \approx 20$, or less than 1 quasar in the 36 deg$^2$ of our survey.

The goal remains to determine the quasar luminosity function at fainter magnitudes. From the SDSS luminosity function over $4.5 < z < 5$ we would expect to find 10 quasars down to $I = 21.5$ and 20 quasars to $I = 22$ in our survey, while the QLF of SSG predicts 15 quasars to $I = 21.5$ and 35 to $I = 22$. Although we implemented candidate selection to $I = 21.5$, in the end we attempted spectroscopy of only five candidates with $I > 21$. None of the resulting spectra were good enough to allow identification, but most likely the objects are stars given the absence of any obvious emission lines. Constraining the number of faint
quasars in our survey may require additional z-band imaging data to reduce the scatter in the color-color diagram at faint magnitudes and enable candidate selection closer to the stellar locus.

Follow-up spectroscopy on the $I > 21$ candidates will also necessitate the use of 8–10 m telescopes to achieve a reasonable efficiency. In addition to the selected candidates down to $I = 21.5$ remaining to be observed, we have identified 275 potential candidates with $21.5 < I < 22$. Of course, effective use of time on the largest telescopes will require additional work to keep cool stars from ending up in the candidate list. As an example, Fan et al. (2001c) used J-band photometry to pare L- and T-type dwarfs from their list of i-band dropouts in a search for quasars at $z \approx 6$.

In summary, to date we have obtained spectroscopic observations of the brightest candidates in our survey for high-redshift quasars. We have not yet found any quasars with $z > 5$, and in hindsight this is not surprising, given the results from SDSS. But the SDSS results also predict that our survey area will contain about five quasars with $z > 5$ to $I = 21.5$ and 11 to $I = 22$. The next important step is to follow up on the fainter objects, which will require observations with 8 m class telescopes.

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