RADIO-SELECTED QUASARS IN THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

We have conducted a pilot survey for \( z > 3.5 \) quasars by combining the FIRST radio survey with the Sloan Digital Sky Survey (SDSS). While SDSS already targets FIRST sources for spectroscopy as quasar candidates, our survey includes fainter quasars and greatly improves the discovery rate by using strict astrometric criteria for matching the radio and optical positions. Our method allows for selection of high-redshift quasars with less color bias than with optical selection, as using radio selection essentially eliminates stellar contamination. We report the results of spectroscopy for 45 candidates, including 29 quasars in the range 0.37 < \( z < 5.2 \), with 7 having redshifts \( z > 3.5 \). We compare quasars selected using radio and optical criteria, and find that radio-selected quasars have a much higher fraction of moderately reddened objects. We derive a radio-loud quasar luminosity function at \( 3.5 < z < 4.0 \), and find that it is in good agreement with expectations from prior SDSS results.

Key words: quasars: general

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1. INTRODUCTION

The first quasars were discovered in radio surveys once it became possible to confidently associate radio sources with optical counterparts that had unusual colors (Schmidt 1963). Subsequently, it was found that quasars could be readily identified on the basis of their optical emission alone (Sandage 1965), as their roughly power-law spectral energy distributions (SEDs) were easily distinguishable from stellar blackbody emission. Optical surveys have since dominated quasar discoveries, while the minority radio population has been used to find highly reddened quasars (Webster et al. 1995; Gregg et al. 2002; White et al. 2003; Glikman et al. 2004, 2007; Urrutia et al. 2009) and scarce, high-redshift quasars (Hook et al. 1995, 1998; Snellen et al. 2001; Benn et al. 2002; Holt et al. 2004; Carballo et al. 2006, 2008; McGreer et al. 2006). In both cases the use of radio data enables searches in regions of color space that are problematic for optical selection alone.

The Sloan Digital Sky Survey (SDSS; York et al. 2000) has assembled the largest collection of quasars to date; the DR5 catalog includes nearly 80,000 quasars found over 8000 deg\(^2\) (Schneider et al. 2007). Before SDSS, only \( \sim 200 \) quasars were known at \( z > 4 \), and none at \( z > 5 \). By targeting roughly \( 10^5 \) objects for spectroscopic follow-up as candidate quasars, the SDSS has been able to uncover even the rarest sources, including \( \sim 60 \) luminous quasars at \( z > 5 \).

Historically, low-redshift quasars were often identified by their ultraviolet-excess relative to stars, and were thus selected from somewhat restricted regions of color space. One of the great advances of the SDSS was to select essentially all objects with stellar morphologies but nonstellar colors as quasar targets, allowing for a variety of quasars to be discovered over a wide range of redshifts, including objects with highly unusual colors (e.g., BALQSOs; Hall et al. 2002). However, quasar colors are not always different from those of stars. This is especially problematic at high redshift (\( z > 2 \)), where quasar colors blend with the stellar distribution. Whether or not a given quasar is selected by the SDSS depends on its flux, redshift, and intrinsic color; thus the selection function can be somewhat difficult to characterize, even if target determination is rather simple.

The sheer yield of quasars from the SDSS demonstrates that the targeting algorithms are highly effective. The completeness of the SDSS quasar survey has been studied in detail by Vanden Berk et al. (2005) and Richards et al. (2006, hereafter R06). The former obtained spectra of \( \sim 20,000 \) stellar objects from 278 deg\(^2\) of SDSS imaging data and found that only 10 were quasars missed by SDSS targeting. The latter used simulated quasar photometry, assuming a Gaussian distribution of power-law quasar SEDs centered on a typical spectral index of \( \alpha_v = -0.5(F_v \propto \nu^{-\alpha_v}) \), to estimate the completeness of the observed quasar distribution with respect to color, luminosity, and redshift. Both studies were most effective at low redshift (\( z < 2.5 \)) due to the relative scarcity of more distant quasars.

The SDSS also considers stellar counterparts to radio sources from the Faint Images of the Radio Sky at Twenty-Centimeters survey (FIRST; Becker et al. 1995) as primary targets. Radio selection of quasar candidates is limited in the sense that radio-bright quasars constitute only \( \sim 10\% \) of the total population, and objects selected by radio emission may not be representative of the population as a whole. However, radio selection avoids many of the problems inherent in color selection, as stars do not contribute significantly to the mJy radio population and are thus easily eliminated from radio samples without regard for color. In this way, radio selection can be used to test the completeness of optical selection.

The apparent connection between black hole growth and galaxy evolution (e.g., Ferrarese & Merritt 2000) underscores the need to understand the evolution of the quasar population over cosmic time. Evolutionary trends in the quasar population are often characterized through luminosity functions, which require a well-understood selection function. The comoving number density of quasars has long been known to evolve strongly with redshift, peaking at \( z \sim 2.5 \) and declining rapidly at higher redshifts. A sample of \( z > 2.75 \) quasars from the Palomar Transit Grism Survey (Schmidt et al. 1995) yielded a flatter slope for the high-\( z \) quasar luminosity function than that derived for low-redshift quasars. The much larger sample of color-selected quasars from the SDSS showed a similar change in the bright-end slope, suggesting an evolution not just in the number density but also the luminosity distribution of high-

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redshift quasars (Fan et al. 2001; Richards et al. 2006). However, there are relatively few probes of the luminous high-z quasar population available for comparison.

In this work we examine the completeness of SDSS quasar selection at $z > 3.5$ by identifying quasar candidates drawn from the combined FIRST and SDSS data. We define a sample of high-z quasar candidates through a simple color cut that selects red SDSS counterparts to FIRST sources. This allows us to explore a wide swath of color space with minimal bias in the optical colors of high-redshift quasars. We achieve a relatively high efficiency of discovery by requiring small offsets between the radio and optical positions, practically eliminating stars from our sample. Our observations fill in gaps in the SDSS quasar selection by targeting fainter counterparts to radio sources.

We begin by summarizing the methods for targeting quasar candidates adopted by the SDSS. We describe our selection criteria in Section 3 and compare the efficiencies of various selection methods. In Section 4, we present spectroscopy for 45 of our candidates, including many new quasars. We place our sample in a broader context in Section 5 by including results from other surveys, following which we discuss a population of moderately reddened quasars at low redshift found primarily through radio selection, and calculate a luminosity function for radio-loud quasars at $3.5 < z < 4.0$. Finally, we present some brief conclusions and prospects for future surveys. We adopt a standard cosmology of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$.

2. SDSS QUASAR SELECTION

As our quasar sample is drawn from the SDSS, we provide a brief review of the algorithms used by SDSS to target quasars for spectroscopy before discussing our method for selecting high-redshift quasars. For a complete description of SDSS quasar selection, see Richards et al. (2002).

The SDSS has two primary criteria for targeting quasars. The first is color selection, with separate criteria for low- and high-redshift targets. The algorithm used to target quasars at $z > 2.5$ is referred to as QSO_TARGET_HIZ. Briefly, stellar sources with $15.0 < i < 20.2$ are targeted when they are far from the stellar locus in $gri$ color space, or if they are within inclusion regions (and outside exclusion regions) used to target quasars at specific redshifts. This leads to a strongly redshift-dependent completeness at high redshift, as quasar colors move in and out of the stellar locus (R06). For brevity, we will refer to the QSO_TARGET_HIZ algorithm as QSO_HIZ.

The second criterion is based on matching stellar SDSS sources to FIRST radio sources; all sources having $15.0 < i < 19.1$ and a FIRST match within $2^\prime$ are selected for spectroscopic follow-up. Targets selected in this manner have the flag QSO_FIRST. First selection allows quasar candidates that fall within the stellar locus or are otherwise missed by color selection to be targeted. However, the brighter magnitude limit adopted for QSO_FIRST selection means that few high-z quasars are identified outside of the QSO_HIZ algorithm—only $\sim 20\%$ of $z > 3$ quasars in DR5 QSO have $i < 19.1$, and only 1 in 10 were targeted outside of QSO_HIZ.

Objects from the SDSS photometric database are rejected as quasar candidates if they have the fatal errors BRIGHT, SATURATED, EDGE, or BLENDED. The first three flags occur for bright objects, bleed trails of bright stars, and objects near the edge of imaging frames. The deblending algorithm separates BLENDED sources into one or more children, each of which is assigned the CHILD flag and is considered by the quasar-targeting algorithm. A primary object with the BLENDED flag indicates that the attempt to deblend was unsuccessful, and thus the object’s photometry is unreliable.

3. RADIO SAMPLE SELECTION

Our survey is designed to identify $z > 3.5$ radio-loud quasars efficiently with a high level of completeness and minimal bias in optical color. Stars are the principal contaminant in optical quasar surveys and must be eliminated to achieve high efficiency. As noted in Section 2, SDSS uses a $2^\prime$ radius to match with FIRST. This results in a high degree of completeness with respect to radio-optical associations, as very few radio quasars have offsets between the optical and radio positions greater than this value. In fact, because of the excellent astrometry of the two surveys, the peak of the optical/radio offsets occurs at about 0.2 (Schneider et al. 2007, Figure 9(a)). On the other hand, the number of stars in the SDSS is so large that using a $2^\prime$ radius to identify radio quasar candidates results in significant stellar contamination. Of the quasar candidates targeted by SDSS using FIRST-only criteria (i.e., having the QSO_FIRST target flag set but no optical selection flags), only 40% are quasars, while over half are stars. This is not due to a large population of stars with mJy radio emission; rather, the stars are clearly offset from the radio positions with a distribution consistent with chance coincidence. Recent work with the SDSS has shown that the number of radio-emitting stars detected by FIRST at faint optical magnitudes is exceedingly small (Kimball et al. 2009).

Subarcsecond matching of FIRST and SDSS sources greatly increases the yield of quasars relative to stars, but does introduce bias against sources near the FIRST detection limit, where the astrometric uncertainties are greater. In addition, for quasars with extended radio counterparts, the fitted radio centroid may not correspond directly to the optical position. We find that using a 0.5 matching radius is $\geq 70\%$ complete to quasars with $S_{1.4} > 2$ mJy; this will be discussed in more detail in Section 6.3.

The strict matching described above allows us to eliminate stars without resorting to color selection techniques, freeing us to select quasars independent of their optical properties. However, if we blindly selected optical counterparts to radio sources, we would be overwhelmed by low-z quasars. To reach the desired population at $z > 3.5$, we take advantage of Ly$\alpha$ forest absorption, which reddens all high-z quasars irrespective of their intrinsic SED. In particular, we expect the ultraviolet forest to be strongly absorbed for $z > 3.5$ quasars, and thus colors in these bands can be used to reduce low-z quasar contamination without introducing much bias at high redshift. A thorough discussion of the changes in quasar colors with redshift in the SDSS photometric system can be found in Richards et al. (2001).

In that work it is noted that at $z > 2.6$, little or no flux is expected in the $u$ band, while at $z > 3.5$, the $g-r$ color reddens as the Ly$\alpha$ forest is in the $g$ band.

We base our selection on the combination of a red $ugr$ color cut with subarcsecond matching of radio and optical positions. In order to expand on SDSS selection, we target objects below the flux limit of QSO_FIRST selection. The sample is drawn from the SDSS DR6 photometric database Best..PhotoObjAll.
The radio flux limit is that of the FIRST survey. Visual examination of the 76 BLENDED objects in our candidate sample showed that nearly all of them were stars, and only 5% are galaxies.  

Visual examination of the spectra will change the classifications of 20% of quasars due to the relative scarcity of the high-redshift population (especially at the brighter limit of $i < 19.1$). Imposing our red $ugr$ color cut results in large numbers of both stars and quasars, but with $z > 3.5$ being much more rare, stars make up nearly 90% of our FIRST-selected sample with red $ugr$ colors. The final result is that over 70% of our FIRST-selected sample with red $ugr$ colors consists of quasars, with nearly 20% at $z > 3.5$.

### 4. OBSERVATIONS

We constructed a sample of candidates meeting the selection criteria of the preceding section and without preexisting spectra (as of the SDSS DR6 release) and obtained low-resolution optical spectra for 45 of these candidates with the 2.4 m Hiltner telescope at MDM Observatory. Objects were selected for observation that were the FIRST sources with red $ugr$ colors. The final result is that over 70% of our FIRST-selected sample with red $ugr$ colors consists of quasars, with nearly 20% at $z > 3.5$.

### Notes

Summary of methods used to identify quasar candidates in the SDSS. Values in each row are extracted from queries to the DR6 SpecObj table. The second column gives the FIRST matching radius for radio selection methods, and the third column gives the number of objects resulting from the query. These objects are subdivided into types based on the output from the automated classification pipeline, with percentages of the total for each row given in parentheses. Visual examination of the spectra will change these results at the few percent level (e.g., Schneider et al. 2007), but the numbers are representative. Note that QSO_FIRST has a limit of $r < 19.1$, while all other methods have a limit of $i < 20.2$.

### Table 1

| Selection     | FIRST (″) | Number | Quasars $z < 3.5$ | Quasars $z > 3.5$ | Stars | Galaxies | Unknown |
|---------------|-----------|--------|------------------|------------------|-------|----------|---------|
| QSO_HIZ       | ...       | 60237  | 17981 (29.9)     | 2859 (4.7)       | 30816 (51.2) | 4371 (7.3) | 4210 (7.0) |
| QSO_HIZ + red | ...       | 37628  | 1731 (4.6)       | 2850 (7.5)       | 25471 (67.3) | 4028 (10.6) | 3748 (9.9) |
| QSO_FIRST     | 2.0       | 5338   | 4137 (77.5)      | 53 (1.0)         | 782 (14.6)  | 125 (2.3)  | 241 (4.5)  |
| FIRST + red   | 2.0       | 1396   | 418 (29.9)       | 131 (9.4)        | 654 (46.8)  | 81 (5.8)   | 112 (8.0)  |
|               | 0.5       | 601    | 313 (52.1)       | 112 (18.6)       | 56 (9.3)    | 40 (6.7)   | 80 (13.3)  |

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$^4$ All SDSS magnitudes quoted in this work are Galactic extinction-corrected PSF magnitudes.
The spectra were reduced using standard IRAF\(^5\) routines called from scripts written in Pyraf.\(^6\) The standard stars HZ44 and BD+284211 were observed each night for flux calibration. Wavelength calibration was provided by Xe and Ar lamps at the beginning and end of each night, though the dispersion was checked (and sometimes corrected) using night sky lines. Cosmic rays were detected in individual images using the L.A. Cosmic routines\(^7\) (van Dokkum 2001) and then masked when the images were combined.

Table 2 provides a catalog of the 45 candidates for which spectra were obtained at MDM. For nine objects, the spectra did not show any identifiable features, but nonzero flux was detected across the full wavelength range sampled and these objects are ruled out as \(z > 3.5\) quasars based on the lack of a Ly\(\alpha\) break.

\(^5\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

\(^6\) Pyraf is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.

\(^7\) http://www.astro.yale.edu/dokkum/lacosmic/
Figure 1. Spectra of quasars with $3 < z < 4$. Most of the $z < 3.5$ are considerably redder than SDSS quasars in the same redshift range, and several show strong BAL features. The spectra are binned to a dispersion of 10 Å for display purposes. Observed wavelengths of common emission lines are marked.

Some of these objects may be quasars at lower redshifts that did not present strong emission lines within the wavelength range covered by the MDM spectra. Two objects presented broad lines without clear identifications and are classified as probable quasars based on the most likely interpretation for the lines. Finally, 34 of the observed candidates have identifiable features and have been assigned redshifts. This includes three stars (7%), two galaxies (4%), and 29 quasars (64%). Of the four BLENDED objects, at least three are quasars, including the fourth highest redshift overall. The three $g$-band dropouts yielded the lowest and highest redshifts. One is a faint galaxy at $z = 0.099$, and the other two are quasars at $z = 4.8$ and $z = 5.2$ (Figures 2 and 3). Of the observed candidates, 15 had redshifts $z > 3$, including seven with $z > 3.5$ (Figures 1–3).

While none of the candidates observed at MDM had published spectra at the time they were observed, several of them have since appeared in Carballo et al. (2008). In that work, neural networks were employed on combined data from FIRST and SDSS to select quasar candidates at $z > 3.6$; not surprisingly, many of their candidates are in common with ours, including six objects observed at MDM. Of these, three are $z > 3$ quasars for which our identifications are in good agreement with theirs (J123128.2+184714, J140635.6+622543, and J172002.1+245548). The other three do not have identifications in Carballo et al. (2008), and include one object also unidentified by us (J120407.8+484548), one star (J170253.5+235758, based on Mg i and Na i absorption), and one quasar at $z = 3.32$ (J123128.2+184714).
The object was not resolved and had a flux ($i_{\text{Mi}}$ in DR5QSO, with a derived luminosity of $1930$ M$_\odot$). The spectrum was obtained in the SDSS. It is also a QSO_HIZ target. This object was observed with CCDS at MDM on 2009 January 6, and on 2008 June 8 a 3600 s spectrum was obtained with the grating centered at 7000 Å in order to capture much of the emission redward of Ly$\alpha$. It is not a primary quasar target in the SDSS.

**4.1. Notes on Individual Sources**

1. **FIRST J163705.1+483601** ($z = 0.099$). One of the three $g$-band dropouts observed at MDM. Identification is based on narrow H$\alpha$ and [O iii] lines. The emission line strengths and radio luminosity are consistent with a mixture of star formation and active galactic nucleus activity.

2. **FIRST J142634.8+543622** ($z = 4.848$). Another $g$ dropout and the second most distant source in the sample (Figure 2). This quasar was first identified with a 900 s spectrum on 2008 June 6, and on 2008 June 8 a 3600 s spectrum was obtained with the grating centered at 7000 Å in order to capture much of the emission redward of Ly$\alpha$. It is not a primary quasar target in the SDSS.

3. **FIRST J074154.7+252029** ($z = 5.194$). A $g$-dropout, but bright enough ($i = 18.5$) to be a QSO_FIRST target, though no spectrum was obtained in the SDSS. It is also a QSO_HIZ target. This object was observed with CCDS at MDM on 2009 January 29 with a 1″ slit, a wavelength range of 5400–9100 Å, and a total exposure time of 4800s. It is brighter than any $z > 5$ quasar in DR5QSO, with a derived luminosity of $M_i = -29$. Two 60 s exposures were obtained in the $i$ band with the Retrocam imager (Morgan et al. 2005) on the MDM 2.4 m. The seeing was 1′′.2. The images were combined with standard IRAF routines. The object was not resolved and had a flux ($i_{\text{MDM}} = 18.5$) in good agreement with the SDSS measurement (based on flux calibration using SDSS stars in the field). Additional high-resolution observations are required to determine if this object has subarcsecond image splitting due to gravitational lensing. It is detected in Two Micron All Sky Survey, with $J = 17.3 \pm 0.2$, $H = 16.3 \pm 0.2$, and $K = 15.9 \pm 0.2$.

**5. DISCUSSION**

One of our goals is to explore the properties of quasars not selected by the SDSS. In this section we compile all available spectroscopic identifications of our candidates, and use this spectroscopic sample to explore the completeness of the SDSS.

It should be noted that our sample is drawn from the same imaging data as the SDSS quasar survey, and thus inherits many of the same limitations as that survey. For example, objects could be missed due to blending issues, lensed quasars could be misclassified as galaxies, and highly extincted sources could fall below the flux limit even if their intrinsic luminosity is high. Our discussion of completeness is thus restricted to stellar objects detected above a given optical flux in the SDSS survey.

As described in the following section, roughly half of the objects in our sample have spectroscopic identifications. The spectroscopic sampling is derived from several sources, including color selection from the SDSS and radio selection from several surveys (including our own). While this sampling is not complete, it is sufficiently high such that we do not expect the population of unidentified objects to differ significantly from those that have been identified; we will justify this assumption for $z > 3.5$ quasars in Section 6.4.

**5.1. Spectroscopic Identifications of Candidates**

The complete set of quasar candidates identified by the selection described in Section 3 includes 1536 objects to a flux limit of $i < 20.2$, covering 7900 deg$^2$ of the overlap between the FIRST and SDSS surveys. A total of 739 candidates have spectroscopic classifications, which we summarize here.

We begin by querying the SDSS DR6 SpecObj database for matches to our candidates, finding a total of 604 spectra. The most recent release of the SDSS quasar catalog is DR5QSO (Schneider et al. 2007) and contains quasars that have been confirmed by visual examination through the DR5 release. For spectra obtained prior to a modified Julian date of 53520 (roughly the cutoff of the DR5QSO catalog), we accept as quasars only those objects with matches in DR5QSO, resulting in 385 quasars and 109 objects rejected as quasars (including stars, galaxies, and unknown classifications). For the remaining spectra from DR6 (110 total), we visually examined the SDSS spectra and confirmed 79 quasars. For the purposes of this work, we are most interested in high-$z$ quasars, and thus in Table 3 we provide a list of 14 quasars from SDSS DR6 that we have verified to have $z > 3.5$. In total, the SDSS provides 464 quasar identifications for our sample, with 107 at $z > 3.5$.

Next, we examine the NED entries for each candidate. From this we find 27 additional quasars, many of which were radio selected from previous surveys. The NED search adds eight quasars at $z > 3.5$. We further include 18 quasar identifications from Carballo et al. (2008), including 16 at $z > 3.5$. Finally, we add our own spectroscopic sample, with 29 quasars at $z < 3.5$ and seven at $z > 3.5$.

A summary of the sample is shown in Table 4. In total, of the 1536 candidates selected by the criteria outlined in Section 3, 739 have spectroscopic identifications and include 538 quasars and 138 $z > 3.5$ quasars. Figure 4 displays the radio fluxes of all quasars in the sample, showing that our selection method
recovered radio quasars over a wide range of fluxes even at high redshifts.

5.2. Comparison with SDSS Selection

Considering the candidate sample as a whole (1536 objects), about 1 in 5 are color selected by SDSS. Since the results presented in Table 1 indicate that ~70% of the sample should consist of quasars based on a close radio source association, we now examine which quasars in our sample are missed by optical selection. We use relative colors to compare our sample with quasars from the SDSS. Relative color is defined as the difference between the color of an individual quasar and the modal color of quasars at the same redshift (Richards et al. 2003). However, it has been debated whether the radio-selected red quasars are indicative of a much larger (radio-faint) population missed by optical surveys, or rather that quasars with luminous radio emission are intrinsically redder on average.

The modal colors for quasars as a function of redshift were obtained from Schneider et al. (2007). Figure 5 shows the modal color of quasars at the same redshift (Richards et al. 2003). Considering the candidate sample as a whole (1536 objects), 739 (57%) have colors Δ(g − i) > 0.8. By comparison, only 2% of DR5QSO are that red. Thus, our selection criteria, which are designed for quasars at z > 3.5, also recover the red tail of lower redshift quasars.

These red, low-redshift quasars are unlikely to be color selected by the SDSS: only 16% of the radio-selected quasars with Δ(g − i) > 0.8 and z < 3 meet the color selection criteria of the SDSS. The low fraction of radio-selected quasars that were also optically selected shows that SDSS color selection is not effective in identifying moderately reddened quasars. This is because reddening removes quasars from ugr (g − i) selection, which is effective at z ≤ 2 (our sample was selected to have little or no u-band flux). In addition, low-redshift quasars are not generally outliers from the stellar locus in griz space, and reddening tends to push the colors along the locus.

5.2.1. Reddened Quasars at z < 3

Our red ugr color criteria select a large number of low-redshift quasars that are much redder than SDSS quasars. Of the 331 quasars with z < 3 in our sample, 254 (77%) have colors Δ(g − i) > 0.8. By comparison, only 2% of DR5QSO are that red. Thus, our selection criteria, which are designed for quasars at z > 3.5, also recover the red tail of lower redshift quasars.

These red, low-redshift quasars are unlikely to be color selected by the SDSS: only 16% of the radio-selected quasars with Δ(g − i) > 0.8 and z < 3 meet the color selection criteria of the SDSS. The low fraction of radio-selected quasars that were also optically selected shows that SDSS color selection is not effective in identifying moderately reddened quasars. This is because reddening removes quasars from ugr (g − i) selection, which is effective at z ≤ 2 (our sample was selected to have little or no u-band flux). In addition, low-redshift quasars are not generally outliers from the stellar locus in griz space, and reddening tends to push the colors along the locus.

Red quasars are necessarily found at faint optical magnitudes, eventually dropping out of optical surveys if the reddening is severe enough. Figure 6 shows the fraction of quasars from DR5QSO with colors redder than Δ(g − i) > 0.8 as a function of observed flux. Only quasars more luminous than $M_i < -23.5$ (uncorrected for absorption) are included in the sample in order to eliminate contaminating light from the host galaxy. The fraction of red quasars increases at fainter fluxes, from ~1.5% at i < 19 to ~3% at i > 19. If only objects with FIRST counterparts are considered, the red fraction is higher across all fluxes, and is nearly 10% at the SDSS survey limit. It is notable that the red fraction among FIRST-detected sources with i > 19.1 is high even though this is below the limit of QSO_FIRST selection in the SDSS. The high fraction of red sources among quasars with FIRST detections implies a relationship between radio emission and optical color.

Radio surveys have been successful at discovering red quasars missed by optical surveys (Webster et al. 1995; White et al. 2003). However, it has been debated whether the radio-selected red quasars are indicative of a much larger (radio-faint) population missed by optical surveys, or rather that quasars with luminous radio emission are intrinsically redder on average. White et al. (2007) found that the median radio loudness in stacked radio images of SDSS quasars increases with redder optical colors (see their Figure 13). This result held even when only the radio emission from optically selected quasars was included in the stack, eliminating any bias from objects selected on the basis of radio detection. Their findings strongly suggest that an intrinsic relationship exists between radio emission and optical color. Interestingly, the stack for the reddest sample they examined (roughly equivalent to Δ(g − i) = 0.8) had a median radio flux density of 0.4 mJy, near the FIRST detection limit. This suggests that the reddest quasars should have a high likelihood of detection by FIRST, consistent with the results presented here.
Several studies have investigated whether the red colors seen in SDSS quasars arise from dust extinction or from an intrinsically red power-law continuum (Richards et al. 2003; Hopkins et al. 2004; Hall et al. 2006; Young et al. 2008).

Dust extinction introduces curvature into the optical spectrum, whereas an intrinsically red continuum would show similar redness in all optical colors. Figure 7 shows the relative $\Delta (g-i)$ and $\Delta (r-z)$ colors for $z < 3$ quasars in our sample compared with DR5QSO. A dust-extincted quasar should have $\Delta (g-i) > \Delta (r-z)$, due to the curvature induced by the shape of the dust absorption spectrum (Hopkins et al. 2004; Hall et al. 2006). Essentially, all of our red quasars have colors consistent with a dust-extincted spectrum. Figure 7 shows the effect of dust reddening on quasar colors using an SMC-type extinction law (Prevot et al. 1984; Pei 1992) with $E(B-V) = 0.1$ and $E(B-V) = 0.5$. The two tracks show the change in colors from $z = 0.6$ to $z = 3.0$ using the QSO spectral template from Vanden Berk et al. (2001). The quasars with $\Delta (g-i) > 0.8$ clearly follow the trend expected for dust reddening with $0.1 \lesssim E(B-V) \lesssim 0.5$. Previous surveys that combined FIRST with infrared data from 2MASS to identify highly reddened quasars (Gregg et al. 2002; Glikman et al. 2004, 2007; Urrutia et al. 2009) typically find larger values of $E(B-V)$. This population can be considered to be only moderately reddened by comparison, and perhaps represents the continued evolution from heavily dust-obscured, Type 2 quasars to the unobscured, Type 1 population with blue optical colors.

5.2.2. Quasars at $z > 3.5$

At high redshift our criteria select quasars with similar colors to those from SDSS. Figure 5 shows that most of the radio-selected sample with $z > 3.5$ has $\Delta (g-i) \sim 0$. At $z > 3.5$, the QSO_HIZ algorithm is very effective; only a handful of quasars identified by other means (usually radio selection) are missed by the algorithm. Of the 138 quasars in our sample with $z > 3.5$, 111 are QSO_HIZ targets, suggesting that the color selection of SDSS is 80% complete in this redshift range. When QSO-FIRST selection is included, the SDSS primary target criteria for quasars select 118 of the $z > 3.5$ sample (86%).
This is in good agreement with the ~85% completeness for SDSS in this redshift range derived by R06.

As noted in Section 4, the MDM sample was drawn uniformly from the set of previously unidentified candidates, other than a preference for objects with \( i \sim 19.5 \). Of the seven \( z > 3.5 \) quasars identified by MDM observations, one had the QSO_FIRST flag, two had the QSO_HIZ flag, and J0741+2520 (at \( z = 5.2 \)) had both flags. These four objects were primary quasar targets in SDSS but did not have spectra obtained in the main survey. One object, at \( z = 3.88 \), was bright enough for QSO_FIRST selection (\( i = 18.7 \)) but had the BLENDED flag set and thus was rejected by the SDSS quasar-targeting pipeline. The remaining two, at \( z = 3.83 \) and \( z = 4.85 \), were too faint for QSO_FIRST selection and were not color-selected. Thus, only three of the 45 candidates observed at MDM were \( z > 3.5 \) quasars missed by SDSS quasar selection.

Figure 8 shows the distribution of our radio-selected quasar sample in the redshift–optical luminosity plane. We derive the absolute magnitude \( M_i(z = 2) \) using the \( k \)-corrections provided in R06; this is the absolute \( i \)-band magnitude for the object if it were at \( z = 2 \). It is clear from this figure that while SDSS color selection is effective in the redshift range we consider (few radio quasars are missed overall), it is much lower at \( z > 3.5 \) than at higher redshifts. Table 5 shows the completeness of SDSS as a function of redshift, measured against our radio-selected sample. QSO_HIZ selection is 80%–90% effective at \( 3.6 < z < 4.0 \), but only ~60% effective at \( 3.5 < z < 3.6 \). This is consistent with the results presented by R06; their Figure 10 shows that the SDSS selection function experiences a local minimum near \( z \sim 3.5 \).

There is a noticeable lack of points in the upper right part of Figure 8, as there appears to be a significant drop in the number of highly luminous quasars with increasing redshift. Some decrease is to be expected, owing to the steep decline in comoving quasar number density with redshift at \( z > 3 \). However, the best-fit luminosity function of R06 predicts a factor of ~2 fewer quasars with \( M_i < -28.3 \) at \( z = 4 \) compared with \( z = 3.5 \), whereas the number of luminous radio-selected quasars in our sample drops by a factor of ~4 over the same redshift interval. These quasars are bright enough for QSO_FIRST selection and should be well-sampled by the SDSS. We estimate the number of luminous quasars detectable by FIRST over this redshift interval by scaling the R06 optical luminosity function by 10% and find reasonable agreement given the limited sample size. Thus, while the drop in highly luminous quasars with redshift is suggestive, the numbers in this study are too small to interpret it further.

6. LUMINOSITY FUNCTION OF 3.5 < \( z < 4.0 \) RADIO-LOUD QUASARS

In the preceding section, we established that our sample of high-redshift quasars is similar to those found by the SDSS. We
now use our sample to construct a luminosity function for radio-loud quasars and compare it with the SDSS results for optically selected quasars. We consider only quasars with $3.5 < z < 4.0$, as our survey was designed to be highly efficient in this redshift range. At higher redshifts, the number of sources is too small to allow meaningful results.

Because we are combining selection from optical and radio surveys with different depths, we define our limiting depth by the ratio of radio and optical fluxes. Thus, we are deriving a luminosity function for quasars which, at a given optical luminosity, have a radio loudness $R^*$ greater than a specified value. We define radio loudness as $R^* = S_{\text{opt}}/S_{\text{5 GHz}}$, in terms of the rest-frame flux densities at 5 GHz and 2500 Å (e.g., Stocke et al. 1992). As the radio and optical fluxes are generally assumed to have the same power-law slope ($\alpha_{\text{rad}} = \alpha_{\text{opt}} = -0.5$) and emission line effects are small over the redshift range under consideration, no formal $k$ correction is necessary when calculating the ratio; however, we do make a slight correction using the assumed slope to bring the observed 1.4 GHz and $i$-band fluxes to rest-frame 5 GHz and 2500 Å. We adopt a limit of $R^* = 70$, which for a quasar with $i = 20.2$ at $z = 4$ corresponds to a 20 cm flux density of $\sim 2$ mJy. Adopting a somewhat high limit in $R^*$ alleviates the incompleteness to the detection of faint radio sources described below, but means that we are not including all radio-loud quasars according to the usual threshold of $R^* > 10$.

Before constructing a luminosity function from our sample, we must first account for several sources of incompleteness.

### 6.1. Optical Detection

At the faint limit of our sample, $i = 20.2$, SDSS is highly complete. In constructing the SDSS QSO luminosity function, R06 applied a 5% correction to account for image quality incompleteness, which arises from objects missed due to fatal and nonfatal photometric errors. The SDSS quasar survey rejects objects with the fatal error BLENDED, whereas we include such objects. By examining roughly two million randomly selected stars from the SDSS with $18.5 < i < 20.2$, we find that $\sim 5\%$ have the BLENDED flag, while $\sim 1\%$ have other fatal photometric errors. These fractions agree well with the occurrence of these errors in our sample (see Section 3). Of the 76 BLENDED objects in our sample, 17 have spectroscopic identifications, 10 of which (59%) are quasars, including 2 (12%) at $z > 3.5$. Thus, the fraction of quasars among BLENDED objects is similar to the sample as a whole. We apply a 1% correction to account for the remaining photometric errors.

### 6.2. Radio Detection

The nominal detection limit of the FIRST survey is 1 mJy. However, the completeness at faint fluxes is different for point and extended sources, and thus the average completeness for a population depends on its angular size distribution. This completeness has been calculated specifically for SDSS quasars and is given in Figure 1 of Jiang et al. (2007). We impose a limit of $S_{1.4} > 2$ mJy for our sample; FIRST is $\gtrsim 85\%$ complete at this limit. We use the curve given in Figure 1 of Jiang et al. (2007) to correct for incompleteness to faint radio sources using the integrated FIRST flux; in general, this correction is small.

### 6.3. Optical/Radio Offset

Our choice of a tight matching radius between the optical and radio positions greatly improves the efficiency of our survey at the expense of completeness. In order to measure this completeness, we identify FIRST counterparts to quasars from DR5QSO using the method of Lu et al. (2007), which accounts for extended and multicomponent radio source counterparts to optical quasars. We consider any FIRST source within 2″ of the optical position as a “core” radio counterpart and allow for “coreless” FRII-type radio counterparts by identifying pairs of radio sources located symmetrically about the optical position with an opening angle $> 150^\circ$ and a total separation $< 2^\prime$ (see Lu et al. 2007; de Vries et al. 2006). In total, we find that $\sim 9\%$ of DR5QSO have FIRST counterparts and $\sim 5\%$ of those do not have a core within 2″.

We then compute the fraction of FIRST counterparts to quasars from DR5QSO that are within 0.5″ of the optical position. Figure 9 shows this distribution as a function of the FIRST flux density. We further divide the sample into extended and compact radio sources, by defining a dimensionless concentration parameter $\theta = (F_{\text{int}}/F_{\text{peak}})^{1/2}$ (Ivezić et al. 2002), which is the geometric mean of the major and minor axis lengths. The concentration is calculated using the peak and integrated flux densities from the FIRST catalog, as measured for the core radio counterpart. Following Kimball & Ivezić (2008), we classify radio sources with a concentration $\theta > 1.06$ as extended and those with $\theta \leq 1.06$ as compact. All coreless radio counterparts are classified as extended.

Over 90% of the quasars in DR5QSO with compact radio counterparts brighter than 5 mJy have optical-radio offsets less than 0.5″. However, at faint radio fluxes, the FIRST astrometric uncertainties increase and a greater number of sources are missed. In addition, the centroid of extended radio sources may not be well-aligned with the optical position, and thus across all radio fluxes we miss a greater number of extended radio sources. About 20%–30% of the FIRST counterparts to SDSS
Spectroscopic coverage of the candidates, expressed as the fraction of candidates per magnitude bin (Δm = 0.2) that have spectroscopic identifications. Most of the spectra come from SDSS, but at i > 19 the coverage drops considerably, as the candidates are too faint for QSO_FIRST selection, and only a small percentage are color selected (QSO_HIZ). Among the candidates with spectra, the fraction of z > 3.5 quasars is roughly constant with i magnitude, at ~17%.

This shows that the spectroscopic coverage of high-z quasars in our sample is high, and we do not expect a significant number of such objects to be left among the objects without spectroscopy.

Quasars that are SDSS primary targets are given a weight of 1/0.81 to account for the spectroscopic incompleteness of the SDSS. For objects that are not primary targets, the fraction that has been observed spectroscopically is strongly dependent on optical flux. We find that the fraction of nonprimary targets with spectra can be described by the linear relation $f_{\text{spec}} = 0.8 - 0.2 \times (i - 17.0)$ (see Figure 10), and thus nonprimary objects are weighted by the inverse of this function. Applying a weight in this fashion assumes that the nonprimary targets with spectroscopic identifications were selected uniformly. We consider this to be a fair assumption as these objects were either serendipitous targets in SDSS or found in radio surveys such as ours that employed broad color criteria.

This weighting is based on the optical flux distribution of the quasars and their luminosities. An alternative method for determining the completeness is to assume a priori distribution in color and absolute magnitude as a function of redshift and then compare with the observed distribution, as was done by R06. We are instead assuming that the candidates with spectra are a fair sample of the remaining unidentified candidates and that our completeness in terms of optical color is high, such that we can estimate the spectroscopic incompleteness simply in terms of the probability that a given candidate has been observed spectroscopically.

6.5. Luminosity Function

Having corrected our sample for all the sources of incompleteness listed above, we now use the sample to calculate a luminosity function for radio-loud quasars at 3.5 < z < 4.0. We derive this function in terms of the optical luminosity in order to compare with results from SDSS. As our sample is limited to luminous quasars ($M_i \lesssim -27$), we model the luminosity function as a single power law, $\Phi_{\text{RL}} \propto L_i^{\beta_{\text{RL}}}$, where RL denotes that we are considering only radio-loud quasars. We construct a binned radio-loud quasar luminosity function (RLQLF) according to the prescription of Page & Carrera (2000), using the $1/V_{\text{max}}$ method (Schmidt 1968; Avni & Bahcall 1980) in discrete magnitude bins. Table 6 and Figure 11 show the resulting RLQLF for radio-loud quasars with $R > 70$ and also compare the values we have derived for radio-loud quasars with those calculated by R06 for quasars from the SDSS.

Overall, there is good agreement between the two luminosity functions, after scaling the optical luminosity function by 5%. The best-fit slope is slightly flatter, with $\beta_{\text{RL}} = -2.2 \pm 0.2$, compared with $\beta \sim -2.4$ as derived by R06 from SDSS data (see their Figure 21). The agreement between the shapes of the luminosity functions provides some corroboration for the assertion that the bright-end slope of the QLF flattens at high redshift (compared with $\beta \sim -3$ at $z \lesssim 2$).

It has been suggested that the fraction of radio-loud quasars (with $R^* > 10$) declines with both redshift and optical luminosity (Jiang et al. 2007). Such an effect might account for the relatively low radio-loud fraction of ~5% derived by comparing the space densities of radio-loud quasars with the optical population (Table 6), as well as the somewhat flatter slope—a decline of the radio-loud fraction with optical luminosity would tend to flatten the RLQLF. However, we note that our sample is restricted to radio-loud quasars with $R^* > 70$ and thus underrepresents the radio-loud fraction according to the threshold usually adopted, which would include objects with $10 < R^* \lesssim 70$. Furthermore,
A wide range of redshifts, and $z$ published for the first time, with seven at matching of the radio and optical positions leads to a high rate $R$. The SDSS QLF, multiplied by 100.

Figure 11. Luminosity function of $3.5 < z < 4.0$ radio-loud quasars with $R^* > 70$, shown as squares with Poisson error bars. For comparison, gray crosses show the luminosity function calculated from SDSS over this redshift interval by R06, scaled by a factor of 0.05 (see Table 6 of R06). The dotted line shows the best-fit slope, $\beta_{RL} = 2.2$.

Table 6

| $M_i$ | $N$ | $N_{RL}$ | $N_{RL}/N_{opt}$ | $\Phi_{RL}$ | $\Phi_{RL}/\Phi_{SDSS}$ |
|-------|-----|----------|------------------|-------------|----------------------|
| $-28.95$ | 7  | 4  | 7.1 | 0.040 | 7.02 |
| $-28.65$ | 13 | 5  | 8.5 | 0.485 | 5.07 |
| $-28.35$ | 13 | 8  | 13.3 | 0.759 | 3.39 |
| $-28.05$ | 16 | 8  | 20.0 | 1.141 | 4.98 |
| $-27.75$ | 21 | 16 | 31.6 | 1.804 | 4.97 |
| $-27.45$ | 20 | 14 | 25.8 | 1.474 | 2.74 |
| $-27.15$ | 19 | 18 | 45.2 | 3.162 | 4.57 |
| $-26.85$ | 4  | 4  | 14.4 | 4.337 | 3.37 |

Notes. Columns are (1) $M_i$, (2) the number of FIRST/SDSS quasars in the bin, (3) the number of radio-loud quasars in the bin ($R > 70$), (4) the corrected number of radio-loud quasars in the bin after applying the incompleteness weights, (5) RLQLF in units of $10^{-9}Mpc^{-3}$mag$^{-1}$, (6) ratio of RLQLF to SDSS QLF; multiplied by 100.

Jiang et al. (2007) found that the radio-loud fraction depends on optical luminosity as $\sim L^{0.5}$, implying that $\beta_{RL} \sim \beta_{SDSS} + 0.5$, which is a greater difference between the two slopes than we find. A larger sample of high-$z$ quasars with radio coverage deeper than that of FIRST is needed to better address this question.

7. CONCLUSIONS

We have assembled a sample of $z > 3.5$ radio quasar candidates using a simple color cut and shown that precise matching of the radio and optical positions leads to a high rate of discovery. We have identified 29 quasars, 26 of which are published for the first time, with seven at $z > 3.5$ and the highest redshift source at $z = 5.2$.

The SDSS does an excellent job of identifying quasars at a wide range of redshifts, and $\sim 85\%$ of $z > 3.5$ quasars in our radio-selected quasar sample were targeted by the color selection algorithms of SDSS. However, it achieves a high degree of completeness at the expense of efficiency, with the primary algorithm used to target high-$z$ quasars having a 50% stellar contamination rate.

We have shown that radio selection, when optimized to the astrometric precisions of the parent surveys and combined with simple, relatively unbiased color selection, can identify high-redshift quasars with high efficiency. Our particular criteria were used to target quasars at $z > 3.5$ and are 20% efficient at those redshifts. Applying red color selection criteria yields two types of objects: low-redshift, moderately reddened quasars largely missed by optical selection, and high-redshift quasars similar to those found in optical surveys. We used our radio-selected sample of $z > 3.5$ quasars to derive a completeness for SDSS selection at high redshift and found the completeness to be high ($\sim 85\%$) and in good agreement with previous results. We further use the sample to derive a radio-loud quasar luminosity function at $3.5 < z < 4.0$, and again find good agreement with SDSS results.

More sophisticated quasar selection methods, such as the automated neural networks employed by Carballo et al. (2008), can achieve even higher efficiencies ($\sim 70\%$). This potentially comes at the expense of completeness, and the selection function can be difficult to quantify. In addition, these methods require a training set of known objects, meaning that the candidates identified by the algorithm will generally have similar properties to the input objects and are subject to any limitations inherent to that sample. Broad criteria such as ours are much less efficient, but better suited for constructing complete samples.

We have employed radio selection in order to expand on color selection techniques. Currently planned synoptic surveys such as PAN-STARRS and LSST will be able to distinguish quasars from stars through optical variability and (lack of) proper motion, and thus find quasars independent of their optical colors. The LSST design will allow detection of quasars to the formal luminosity cutoff ($M < -23$) to $z \sim 5$ without using color selection (Ivezić et al. 2008). Moderately reddened quasars similar to those presented here will fall within reach of this survey. However, for some heavily extincted quasars the nucleus may be sufficiently obscured such that any variability would pass unnoticed, or worse, the observed flux would fall below the survey detection limit. These quasars can be found through infrared-excess selection (IRX; Warren et al. 2000), which is relatively insensitive to reddening, using a new generation of infrared surveys much deeper than 2MASS (e.g., UKIDSS, VIKING, VHS; for an example with UKIDSS see Maddox et al. 2008). These surveys will better address the connection between radio luminosity and optical color by having sensitivity to red quasars without requiring radio detection for selection. Finally, FIRST only detects the most radio-loud quasars at high redshift; future surveys with the greatly enhanced sensitivity of the EVLA will push deeper into the radio-loud quasar luminosity function at high-$z$.

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