We present simulations of quasar colors, magnitudes, and numbers at redshifts 5 < z < 10 based on our discovery of 10 new high-redshift quasars and the cloning of lower redshift Sloan Digital Sky Survey (SDSS) quasars. The 10 quasars have redshifts ranging from z = 4.7 to 5.3 and i magnitudes of 20.21–20.94. The natural diversity of spectral features in the cloned sample allows more realistic simulation of the quasar locus width than was previously possible with synthetic template spectra. Colors are generated for the z > 6 epoch, taking advantage of the new UKIRT Infrared Deep Sky Survey near-infrared filter set, and we examine the redshift intervals of maximum productivity, discussing color selection and survey depth issues. On the basis of the SDSS sample, we find that the surface density of z > 4.7 quasars increases by a factor of 3 times by extending 0.7 i magnitudes deeper than the SDSS spectroscopic survey limit of i = 20.2; correspondingly, we predict a total of ~400 faint quasars in the SDSS main area that have redshift z > 4.7 and magnitudes i < 20.9.

Key words: quasars: emission lines — quasars: general

Online material: color figure

1. INTRODUCTION

In the past decade, the study of distant quasars has proliferated with the happy coincidence of large telescope availability, advanced imaging systems, and wide-area digital sky surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Two Degree Field Quasar Survey (2QZ, Boyle et al. 2000). These factors have changed our understanding of quasars from a few special objects into significant beacons of the distant universe. The productive searches for quasars have fueled cosmological advances, among them, for example, the search for the epoch of hydrogen reionization in the distant universe. With the SDSS discovery of luminous quasars at redshift z ~ 5 (Fan et al. 1999; Zheng et al. 2000) and a leap to quasars at redshift z ~ 6 soon after (Fan et al. 2001a), the uncertainty of this important epoch has been steadily reduced. And through compilations of uniform catalogs of quasars, the distant and faint quasar luminosity function continues to be extended (SDSS, Schneider et al. 2003; 2QZ, Croom et al. 2004).

Will new ground-based infrared surveys reproduce the spectacular quasar discoveries of the past 5 years? How many quasars will deeper and redder surveys find? As the next generation of near-infrared surveys prepares to begin observations, these questions are of keen interest to survey teams and observers pursuing increasingly higher redshifts. Cosmologists, too, speculate on how far back it will be possible to push the earliest formation of the dark halos necessary for quasar activity and whether the first epoch of star formation and chemical evolution will someday be glimpsed.

The schedule of new optical/infrared surveys suggests that z > 6 objects will still be sparse for several more years. The recently discovered SDSS z ~ 6 objects represent only the brightest fraction of the population at this distance and are quite rare—12 discovered to date within ~4500 deg 2 at z-band magnitudes <20.2 (Fan et al. 2004). With no fainter large-area optical surveys planned for the near future, the best hope of increasing such quasar numbers appears to be through deep pencil-beam studies. Deep imaging wells have been drilled in the optical, such as in the Hubble Ultra Deep Field, and near-infrared surveys like the UKIRT Infrared Deep Sky Survey (UKIDSS) also plan to dedicate time to faint observations that may reach as deep as J = 25.

With few faint objects at high redshift to guide such observational efforts, valuable information about the high-redshift quasar luminosity function as a function of magnitude may be elucidated from more abundant numbers at z < 6. The properties of lower redshift quasars can predict the limiting magnitude of the observations needed to find the first z ~ 7 quasar and even beyond, filling in the statistical deficiencies accompanying such small populations. Low-redshift quasars can be used to effectively target yet unseen objects, a task that requires an understanding of expected color, magnitude, and completeness.

The cloning of quasar spectra provides a tool to predict these parameters. As the historical barriers of z = 4, 5, and 6 have been broken, these observational advances have confirmed a valuable result—the spectra of quasars at high redshift look much like those of quasars nearby (Fan et al. 2004). In this work, we exploit the similarity of near and distant quasars to simulate and predict the color properties of the next generation of objects at z ~ 7 and above. Past quasar selections have generally relied on composite quasar spectra. Here, by contrast, we take advantage of the natural diversity of a low-redshift population to preserve the possible range of high-redshift quasar colors. We employ nearby quasars discovered in the SDSS to clone samples of higher redshift quasars, in which the natural rarity of such objects makes
analysis and prediction of properties otherwise difficult. And with a sample of 10 newly discovered faint quasars at \( z \approx 5 \), we illustrate how such faint objects can provide magnitude and completeness information, unhindered by stellar contamination issues when coupled with semisynthetic cloned spectra.

2. SIMULATING \( z \approx 5, 6, \) AND ABOVE: GENERAL METHOD

In this paper we discuss, in order of increasing redshift, three groups of quasars and their color simulations: (1) quasars at \( z \approx 5 \) that are discovered through \( rz \) imaging of the SDSS, including 10 newly observed here, (2) quasars at \( z \approx 6 \) that are discovered through \( iz \) imaging in the SDSS and independent \( J \) imaging in the near-infrared, and (3) quasars yet to be discovered at \( z > 6.5 \) that will rely on a new infrared filter system such as the UKIDSS ZYJHK. We focus on these three epochs because, as much by fortune as by design, the optical and infrared filter sets combined with the colors of stars and quasars conspire to make these redshifts of prime interest and productivity for quasar observers.

2.1. Quasar Color Behavior

Simulations of quasar colors to date have generally relied on the redshifting of synthetic model spectra. The color behavior of quasars with increasing redshift is simple to predict in a very general way. The interstellar medium along the line of sight removes flux from any background source object, and as increasingly higher redshifts are probed, absorption from gas at each intervening redshift progressively damps the spectrum, becoming more severe with redshift. Of relevance here is hydrogen \( \text{Ly}_\alpha \) at 1216 Å; as the \( \text{Ly}_\alpha \) break increases in wavelength with redshift and passes through neighboring photometric bands, the color difference \( (m_{\text{blue}} - m_{\text{red}}) \) can usually be expected to increase monotonically until the \( \text{Ly}_\alpha \) break reaches the effective end of the first filter.

However, to calculate accurate color behavior requires modeling the quasar spectrum or the use of real quasar data. The prediction of quasar colors in three bands—which is most useful for detailed target selection through color-color limits—can be very sensitive to spectral features. While diversity has been simulated in some synthetic models of quasars, including variations in emission and absorption lines as well as continuum properties, the natural diversity of quasars is much preferred.

In each of these three redshift regimes, we produce semisynthetic colors of distant quasars by using the known spectra of quasars at lower redshifts. This procedure, called cloning, has been previously employed to simulate the images of high-redshift galaxies and aid photometric target selection, such as in Bouwens et al. (1998a, 1998b). Here we simulate the spectra of high-redshift quasars by taking a large number of spectroscopically observed quasars at a lower redshift, numerically shifting those spectra to a desired higher redshift (where the real sample is otherwise sparse), and determining the resulting expected colors through selected broadband filters. When a digital catalog of well-classified spectra is available, this technique is straightforward yet powerful and allows a simulation of quasar properties that need only be “semisynthetic.” Diversity of spectral features is naturally introduced through the low-redshift quasar sample itself and propagated to higher redshift without large uncertainties or assumptions regarding the range of possible quasar attributes.

We emphasize that the capability to clone quasars without having to consider intrinsic quasar evolution need not be the case. For example, galaxy spectra at high redshift may be significantly different from the galaxies that are familiar in the local neighborhood; cloning such populations to high redshift actually yields an empirical measure of galaxy evolution when combined with observation. Luckily, we are aided by the observation that quasars even at redshifts above \( z = 6 \) display the same general spectral features as those at \( z = 2 \), for instance.

2.2. Spectral Data Source and Cloning Procedure

In this work, we use the SDSS First Data Release (DR1) Quasar Catalog generated by Schneider et al. (2003), which covers 1360 deg\(^2\) and contains 16,713 quasars. The DR1 Quasar Catalog is a compilation of quasars confirmed by the SDSS automated spectroscopic program, which reaches \( z = 5.41 \) in redshift and ranges from 15.15 to 21.78 in \( i \) magnitude. The source imaging data for this catalog was taken from MJD 51,075 to 52,522. The hardware and software pipelines producing the final superb photometry and astrometry of the survey have been described by the project collaborators elsewhere in detail: York et al. (2000), Fukugita et al. (1996), Gunn et al. (1998), Hogg et al. (2001), Lupton et al. (1999), Stoughton et al. (2002), Smith et al. (2002), Pier et al. (2003), and Abazajian et al. (2004).

In each of the three redshift ranges, we began by selecting a subset of quasars from the DR1 Quasar Catalog. These selections chose objects optimally suited for cloning—the main criteria were that quasars would be of high enough redshift to display \( \text{Ly}_\alpha \) and that the cloned spectrum would have generally complete flux in the filters of interest. It is worth recalling here that the raw SDSS spectra do not cover the full wavelength range of the SDSS imaging filter system—i.e., the spectra are incomplete at the extremes of the \( u \) and \( z \) filters. Thus, during the generation of any synthetic photometry, care must be taken to ensure that spectral data exist down to 3000 Å and up to 11230 Å (if data are desired in the \( u \) and \( z \) filters). Table 1 shows the number of quasars used in each of the three cloning procedures, the filters covered, the redshift range from which quasars were extracted, and the redshift range of quasar clones produced.

Each original SDSS spectrum was first smoothed by 5 pixels and then redshifted to the range of interest in 0.1 redshift bins. During the redshifting procedure, the quasars were examined for the presence of flux at the extreme wavelengths of the filter set being tested. For those quasars that were not complete down to the bluest filter or up to the reddest filter after redshifting, the data were extended synthetically by fitting and continuing the nearby quasar continuum level. For example, 73% of the quasars at \( z \approx 6 \) required some extension of the data, but on average, only 200 pixels of data were added to the \( \sim 3800 \) pixels in each original SDSS spectrum. This technique allowed a larger number of quasars with a larger redshift range to be used. Without such data extension, only quasars from much narrower ranges of redshifts would have been suitable for cloning, narrowing the diversity of spectral features.

The effect of \( \text{Ly}_\alpha \) absorption at high redshift was added by computing the difference in absorber optical depth between the redshift of the original quasar and the desired cloned quasar,
adapted from the opacity behavior described by Haardt & Madau (1996). The appropriate average decrement was applied to each wavelength in the original data below the rest wavelength Ly\(\alpha\). We neglected the contribution from Lyman limit systems—at all redshifts in these calculations, the rest wavelength 912 Å fell outside the filters of relevance. At redshifts \(z > 6.0\), complete Ly\(\alpha\) damping was applied to the data, i.e., Gunn-Peterson absorption (Gunn & Peterson 1965).

Finally, the synthetic magnitudes of each spectrum were computed in the relevant filters. The SDSS ugriz filter response functions are publicly available at the SDSS Web site, while the UKIDSS response functions (not yet publicly available) were generated by modeling the imaging system. Filter curves for the new UKIDSS ZYJHK filters were obtained from the UKIDSS Web site and multiplied by typical HAWAII-2 HgCdTe detector efficiency curves and the near-infrared atmospheric transmission function produced by the ATRAN program for average conditions (Lord 1992). While computation of the absolute system efficiency requires additional multiplication by mirror reflections and secondary optical effects, these further steps were not applied because broadband colors are not affected by wavelength-independent factors.

The synthetic magnitudes were calculated according to the AB magnitude system described by Oke & Gunn (1983) and illustrated in Blanton et al. (2003):

\[
m_{AB} = -2.41 - 2.5 \log_{10} \left[ \int_0^{\infty} \frac{d\lambda}{\lambda} f(\lambda) R(\lambda) \right].
\]

Although optical AB magnitudes are used by the SDSS, infrared photometry is frequently expressed in Vega-based (Johnson) magnitudes. In this work we employ both systems for ease of use by observers and note that an additive factor is needed to convert between the two. For reference, the appropriate transformation between AB and Vega magnitudes is given by the equation \(m_{Vega} = m_{AB} + c\), where \(c\) is an additive correction dependent on wavelength and spectral energy distribution; we used \(c = [-0.50, -0.64, -0.90, -1.38, -1.84]\) in the five UKIDSS filters \(Z, Y, J, H,\) and \(K\) based on a model quasar continuum of \(f_\nu \propto \nu^{-0.5}\).

In addition to the colors of the individual quasars, statistics of the samples versus redshift were compiled. In all of the color versus redshift plots that follow, we show the median (50%) quasar track accompanied by 1%, 5%, 15%, 85%, 95%, and 99% values of 741 cloned quasars at redshifts \(4.4 \leq z \leq 5.8\). The SDSS riz filter curves, with the abscissa wavelength scale matching quasar redshift (Ly\(\alpha\) break), are also shown. Magnitudes are expressed in the SDSS asinh (AB) system. The strong 7600 Å absorption in the SDSS i filter is due to the atmospheric A band.

3. QUASARS AT \(z \sim 5\)

The \(z \sim 5\) epoch has been a highly productive area for quasar discovery in recent years, with most of the advances originating from SDSS imaging data. As shown in Figure 1 (bottom), quasars at these redshifts are identified in the SDSS riz filters and, as seen in Figure 2 (bottom), are successfully targeted because of their separation from the stellar locus in two-color space.

However, not all quasars are observable because of the practical issue of stellar contamination, and in fact, it is this that imposes the upper redshift limit on the SDSS automated quasar spectroscopic program. While the survey is, in principle, sensitive to quasars up to redshift \(z = 5.8\), stars overwhelm any color-selected observations beginning at \(z = 5.4\). Only two quasars have been discovered in the broad range \(5.4 < z < 5.8\) because of this problem (Stern et al. 2000; Romani et al. 2004). Any successful quasar search based on colors must avoid such contaminants, which drive down spectroscopic follow-up efficiency; therefore, at certain redshifts, such quasar programs will be necessarily incomplete.

3.1. Quasar Completeness at \(z \sim 5\)

A primary goal of our quasar simulation work was to improve the completeness estimates of the SDSS quasar discovery rate. There are only a few dozen known quasars at \(z \sim 5\), which places large errors on any statistics and completeness estimates. With 741 cloned quasars, we can now estimate the SDSS selection completeness with higher precision.

For the 741 quasars cloned to simulate the quasar track from \(z = 4.4\) to 5.8, we have plotted the median \(r - i\) and \(i - z\) colors versus redshift, as well as the entire sample (741 \(\times 15\) objects) in \((r - i, \ i - z)\) to show the width of the distribution (Fig. 2, top). Two quasar selection areas are also plotted: The first (slanted top) is that of the SDSS high-redshift quasar program, defined by the boundaries \(r - i > 0.6,\ i - z > -1.0,\) and \(i - z < 0.5(r - i) - 0.412\). The smaller box is the selection used later in this work, \(r - i > 1.7\) and \(i - z < 0.2,\) which is explained in § 3.2. In Figure 2 (bottom) the riz stellar locus and our median quasar track have been plotted for comparison.

For each redshift from 4.4 to 5.5, we then calculated the fraction of the 741 cloned quasars falling in the SDSS selection, as well as in our smaller selection region. The SDSS high-z quasar target selection is very successful, with a peak efficiency (quasar fraction captured) of 98.2% at redshift \(z = 4.7\). Our smaller selection region, by comparison, has a peak of 41% at \(z = 4.8\), but despite its lower absolute efficiency, its utility is illustrated in the accompanying observations we undertook. These efficiency curves are shown in Figure 3 (top).

3.2. Observing Quasars at \(z \sim 5\):10 Newly Discovered Objects

We used these completeness results to design an observing program that successfully targeted faint \(z \sim 5\) quasars with high efficiency. The observational challenge of finding \(z \sim 5\) quasars is relatively straightforward, although time intensive—it involves selecting a suitable color sample of candidates, eliminating the
bulk of contaminants, and carrying out spectroscopy. With such a sample of faint quasars, we hoped to estimate the potential discoverable quasar pool in the SDSS imaging and make predictions about the future quasar discovery rates. Other attributes of such a faint program are a significant increase in quasar candidate numbers and a larger resulting population of confirmed quasars. In addition, a fainter quasar candidate selection can be expected to yield a population of slightly higher redshift objects than a brighter sample, because of the intrinsic luminosity properties of quasars.

Using SDSS imaging data observed from 2000 September to 2004 March, we performed the candidate selection, consisting of the aforementioned color cut and a magnitude cut on point-source objects identified by the SDSS photometric pipeline, with precautions against false detections. For the purpose of identifying quasars at $z \sim 5$, we safely restricted our sample to point sources only—of the quasars discovered automatically by the SDSS DR1 quasar survey, only 5.4% of the total sample (913 of 17,613) are classified as extended. Above a redshift of $z = 2.0$, the proportion falls more dramatically—extended sources represent only 24 out of 3218 quasars. By $z = 4.0$ and greater, only one quasar out of 187 is classified as extended.

We applied the requirement for $u$ and $g$ blank detections to the data while also limiting the $i$-magnitude selection to $20.2 < i < 21.0$. The asinh modified AB magnitude system of Lupton et al. (1999) produces reasonable magnitudes even at extremely low instrumental flux levels, which is critical for work near the survey flux limits. The range $20.2 < i < 21.0$ represents that unexamined by the SDSS spectroscopic target selection, down to the faintness limit of our spectroscopic capability (Richards et al. 2002). The color cut, $r - i > 1.7$ and $i - z < 0.2$, was designed to produce a higher average redshift sample than could be expected from the SDSS main survey quasar selection, while decreasing the fraction of stars and other contaminants in the follow-up observations.

A final measure ensuring high discovery efficiency during spectroscopic follow-up was the application of SDSS photometric flag screens to eliminate objects tainted by faulty photometry. The simple application of color cuts alone often results in the retrieval of objects or artifacts dominated by cosmic rays, chip artifacts, moving sources, and other photometric errors. Judicious application of flag requirements (such as excluding BRIGHT, EDGE, SATURATED, CHILD, and CR) eliminates most blatant problems while not excluding real sources. Cosmic-ray hits represented the bulk of remaining contaminants in our samples—these were further removed through visual inspection.

The candidates were observed using the Double Imaging Spectrograph at the Apache Point Observatory (APO) 3.5 m telescope, the FOCAS instrument (Kashikawa et al. 2002) of the Subaru Telescope (Iye et al. 2004) at Mauna Kea, and the
Low-Resolution Spectrograph (Hill et al. 1998) of the Hobby-Eberly Telescope (HET). Observational notes for individual objects are detailed here, and finding charts and spectra appear in Figures 4 and 5. The typical exposure time was 1200 s with APO, or 300 s with Subaru, and the spectral resolution was 2.5 Å over the range 5200–9500 Å. In the case of quasar J084802.82+342715.3 (z = 4.73), the intrinsic faintness of the object (i = 20.9), combined with moderate to poor seeing and a minor tracking problem, reduced flux. Redshifts were determined by the SPECFIT program, with a fit of each smoothed quasar spectrum by a continuum, N v and Ly/ C11 emission, and absorption blueward of Ly. The observed quasar properties are listed in Table 2.

3.3. Discussion of Sky Coverage and Statistics

A comparison of these 10 quasars with quasars from the SDSS DR1 Quasar Catalog reveals that, as expected, a deeper spectroscopic observing program increases discovered quasar numbers by several fold. We evaluate and quantify these gains here.

The 10 quasars described in this work were found in a searched sky coverage of approximately 656 deg². The SDSS imaging scheme causes some sky area to be multiply imaged, and it is therefore necessary to calculate the total area searched as the unique footprint of the combined imaging runs, rather than their simple sum. The simple overlapping areas searched in this work made such a calculation straightforward, but a more sophisticated calculation, such as Monte Carlo sphere filling, will be appropriate in future samples covering substantial and non-trivially overlapping areas. Specifically, it must account for the 10% overlap between strips and curved converging areas near the beginnings and ends of complete strips at the survey poles (such as in Fan et al. 2001a). In this analysis, such effects are small compared to the 10¹/² Poisson noise of the sample size.

As with the quasar cloning procedure, we use as a reference and comparison work the SDSS DR1 Quasar Catalog. Of relevance to this analysis are quasars produced by the SDSS high-z quasar target selection, which automatically selects targets expected to be of redshift z > 4.5 from SDSS photometric data. The DR1 contains 35 such quasars, from redshifts z = 4.56 to 5.41 with magnitudes from i = 18.33 to 20.47. Nineteen of these quasars have redshifts above z = 4.7 and i magnitudes within the SDSS spectroscopic survey limit of i = 20.2.

We find that our sample of 10 z ~ 5 quasars is statistically consistent with the DR1 population of high-redshift quasars. In Figure 2, we superpose in (r - i, i - z) two-color space the 24 DR1 quasars with redshift greater than 4.7 along with the 10 quasars found in this work. Our color selection criteria (rectangular box: r - i > 1.7, i - z < 0.2) and the SDSS high-z selection criteria (slanted top: r - i > 0.6, i - z > -1.0, and
are also shown. Now examining only quasars that would be selected by both our and the SDSS quasar color criteria, we find seven DR1 objects for comparison, which range from redshifts $z = 4.69$ to 5.12 and magnitudes $i = 18.63$ to 20.45. Using the relative areas of each sample to compare the confirmed quasars in this specific color selection (1360 vs. 656 deg$^2$), we find that our sample produces 2.96 times the number of DR1 quasars per normalized area. We attribute this gain to the fainter magnitude limit of our work, which reaches 0.7 $i$ magnitudes deeper than the SDSS main survey. This result accords well with the work of Fan et al. (2001b), for example, who described a number density increase of a factor of $\sim 4$ mag$^{-1}$, for quasars at $z > 4.0$.

Treating the redshift range from $z = 4.7$ to 5.2 as one bin, we find a color selection completeness of 20% in our work versus 76% in the SDSS target selection by this measure. Quasars selected by our target selection region represent 26% of the sample selected by the SDSS quasar-targeting algorithm. This factor is not statistically very different from the seven quasars out of 24 (29%) found at redshifts $z > 4.7$ in the DR1 Quasar Catalog.

### 3.4. Additional Object Discovery Rate

A perfectly complete quasar luminosity function would specify quasar numbers at all redshifts, at all intrinsic brightnesses, and with low statistical errors. In reality, however, the faintness limits of observations and the natural rarity of quasars force a slightly less ideal specification of the luminosity function. Extending the quasar luminosity function to high redshifts and faint magnitudes is thus a primary goal of large-area quasar surveys. Recent work, such as that from 2QZ and the SDSS (Croom et al. 2004; Schneider et al. 2003), has extended the knowledge of quasar density down to $M_b = -22$ and up to redshift $z = 2.3$.

### Table 2

Properties of 10 $z > 4.7$ Quasars Found in This Work

| Object                | Redshift $z$ | $r$       | $i$       | $z$       |
|-----------------------|--------------|-----------|-----------|-----------|
| J013326.84+010637.7   | 5.30 ± 0.01  | 22.56 ± 0.45 | 20.69 ± 0.05 | 20.48 ± 0.16 |
| J074653.44+470517.6   | 4.84 ± 0.01  | 22.32 ± 0.17 | 20.20 ± 0.05 | 20.22 ± 0.17 |
| J083317.66+272629.0   | 5.02 ± 0.01  | 22.42 ± 0.16 | 20.25 ± 0.04 | 20.23 ± 0.12 |
| J084802.82+342715.3   | 4.73 ± 0.01  | 22.65 ± 0.16 | 20.87 ± 0.05 | 20.75 ± 0.15 |
| J090059.51+274557.6   | 4.96 ± 0.01  | 22.94 ± 0.36 | 20.94 ± 0.09 | 20.93 ± 0.30 |
| J134141.46+461110.3   | 5.01 ± 0.01  | 22.19 ± 0.13 | 20.21 ± 0.04 | 20.37 ± 0.15 |
| J141026.22+385652.6   | 4.75 ± 0.01  | 22.03 ± 0.11 | 20.23 ± 0.04 | 20.41 ± 0.15 |
| J152404.10+081639.3   | 5.08 ± 0.01  | 22.81 ± 0.20 | 20.69 ± 0.04 | 20.51 ± 0.11 |
| J155422.97+303214.4   | 4.84 ± 0.01  | 23.84 ± 0.45 | 20.64 ± 0.05 | 20.73 ± 0.18 |
| J211928.32+102906.6   | 5.18 ± 0.01  | 22.32 ± 0.12 | 20.62 ± 0.04 | 20.56 ± 0.15 |

Note.—Double entries indicate quasar detected in more than one imaging run.
and continues to press farther and fainter with deep spectroscopic follow-up observations.

Although the \( z \sim 5 \) quasar luminosity function will be poorly populated for some time, we can still estimate the numbers of quasars that can be found in future searches, using information from cloned quasar colors and the 10 quasars found in this work. Given the SDSS ultimate goal of 10,000 deg\(^2\) of imaging, we expect a total of roughly 140 quasars eventually to be found with redshift \( z > 4.7 \) and magnitude \( i < 20.2 \) out of an ideal sample of 182 that, in principle, could be observed by the SDSS spectrographs if not for stellar contamination. Further pursuit of faint quasars down to \( i \sim 20.9 \), such as those selected in this work, would yield by the same calculation a total of 109 objects from our smaller color selection alone or 414 in the larger SDSS high-\( z \) color selection region.

One goal of the SDSS is to release deep imaging of the southern equatorial region, created from co-adds of areas multiply imaged over several years. These regions have been imaged variously from 3 to 18 times the normal survey exposure time, and an imaging depth of up to roughly 2.5 log(18)\(^{1/2}\) = 1.56 mag is expected. From our limited sample here, we predict that such a depth increase could yield a quasar discovery rate up to ~11 times that of the SDSS main survey. We anticipate that follow-up spectroscopy within these deep areas will provide interesting tests of the quasar statistics and magnitude-number relations presented here, as well as shed new and much needed light on the high-redshift quasar luminosity function.

### 4. QUASARS AT \( z \sim 6 \)

The SDSS imaging survey broke new ground by extending high-quality imaging into the near-infrared with the SDSS \( z \) filter. The relatively deep optical photometry, combined with follow-up infrared observations, allowed the discoveries of quasars for the first time at \( z \sim 6 \) (Fan et al. 2001a, 2003, 2004). In a similar way to that for the quasars at \( z = 5 \), quasars at \( z = 6 \) are identified by their color separation from the contaminating stellar locus. (Although in fact the “contaminants” of \( z = 6 \) quasar searches are L- and T-dwarf stars, rare and interesting in their own right.) However, quasars at \( z = 6 \) tax the observational stamina with the absolute rarity of objects, as well as the challenge of flux in only one optical band, SDSS \( z \). Quasar candidates at \( z > 5.8 \) are /\( i \) dropouts and, as high-risk single-band detections, must be targeted and followed “manually”; recent discoveries of quasars at \( z \sim 6 \) have all been made through dedicated traditional spectroscopic follow-up rather than by an automated survey mode.

To understand the completeness of the \( z \sim 6 \) quasars discovered to date, we simulated the colors of 756 cloned quasars in the SDSS \( i-z \) and UKIDSS \( J \) filters, according to the procedure introduced in the preceding sections. Figure 6 shows the evolution of the \( i-z \) and \( z-J \) colors. The sample begins at redshift \( z = 5.5 \), where the quasar Ly\( \alpha \) (now at \( \lambda 7900 \AA \)) has already been redshifted through much of the SDSS \( i \) filter. As the quasars continue to redshift through the remaining portion of the \( i \) band, measured \( i \) flux drops rapidly, while the Ly\( \alpha \) peak quickly brings flux into the \( z \) band. Thus, within 0.3 redshift units, by 8300 \( \AA \) (\( z = 5.8 \)), the \( i-z \) color has experienced thebulk of its increase—from 0.92 to 2.41. After this point the \( i-z \) value saturates, with some small fluctuations as remaining flux blueward of Ly\( \alpha \) moves through the \( i \) band. By contrast, because of the extreme width of the SDSS \( z \) filter, the \( z-J \) increase is gradual compared to the rapid rise in \( i-z \), although ultimately similar in magnitude. We follow the quasar \( z-J \) value from \( z = 5.7 \) to 7.0, where the Ly\( \alpha \) has reached 9700 \( \AA \), nearly the red edge of the \( z \) filter.

The 756 \( \times 16 = 12,096 \) \( (i-z, z-J) \) points are shown in Figure 7 (top) along with the successful high-redshift quasar color selection region of Fan et al. (2001a, 2003, 2004), which chooses colors \( i-z > 2.2 \) and \( z-J < 1.5 + 0.35(i-z-2.2) \). Dwarf stars from Hawley et al. (2002), Leggett et al. (2002), and Knapp et al. (2004) are also shown, tracing the now very red stellar locus. In Figure 7 (bottom), the condensed median track of the 756 cloned quasars is plotted with labels showing redshift evolution, again plotted with the selection region of Fan et al. Superposed are the 10 quasars at \( z > 5.8 \) discovered by them over the past 3 yr using this selection (stars; one quasar without \( J \) photometry is omitted).

The quasar color selection used by Fan et al. (2003) is necessarily optimized for a particular redshift range. Using the same procedure as detailed for the \( z \sim 5 \) quasars, we computed the redshift of peak selection effectiveness, again defined by the fraction of cloned quasars selected at each redshift bin. This is shown in Figure 8. The peak of the Fan et al. selection occurs at \( 5.8 < z < 6.2 \), with 90%-95% of objects selected, not accounting for contamination by stars. Neither does this account for flux limitations of the survey, which tend to decrease the effectiveness of selection with higher redshifts. Efficiency decreases from the peak at \( z = 5.9 \) to practically zero by redshifts 5.65 and 6.5.

The \( i-z/J \) quasar evolution track found by our simulations is very similar to that of Fan et al. (2003), although some small deviations occur from \( z = 5.6 \) to 5.9 and at \( z > 6.3 \). The model quasar track of Fan et al. departs from our track beginning at \( z = 5.5 \), separating by a maximum of \( z-J = 0.3 \) at \( z = 5.9 \). This difference falls within the first lower \( i-J \) error surface at \( z = 5.9 \), and we attribute it to strong emission-line properties of our sample. In Figure 9, we show a median \( z = 7.0 \) quasar found in our cloned population.

### 5. QUASARS AT \( z > 6.5 \)

As quasars approach redshift \( z = 6.5 \), the SDSS reaches the limits of its observational capabilities. Both the fading apparent
magnitudes of quasars at this distance and the fading quantum efficiency of CCD imaging at 1 \mu m conspire to hinder further discoveries of quasars at higher redshifts. Thus, the discovery of quasars at z > 6.5 will mainly depend on ongoing deeper near-infrared surveys.

5.1. ZYJHK and Future High-Redshift Quasar Selection

The UKIDSS ZYJHK filter system was developed in part to allow the next generation of quasars at z > 6.5 to be discovered. Most significantly, the novel Z and Y filters fill the large gap existing between the SDSS z and near-infrared J bands with sharp-cutoff bandpasses. This stretch of wavelength is of great importance for the discovery of z > 6.5 quasars, because the Ly\alpha break must be observed straddling two adjacent bands in order to select targets with high certainty. Quasars at z = 7.0, for example, fall squarely in the gap between SDSS z and near-infrared J but are rescued by the new Y filter. Combined with the high quantum efficiency of HAWAII HgCdTe detectors from 0.78 to 2.6 \mu m, this system is typical of the future capability of infrared surveys.

To date, one model of quasar colors in ZYJH has been advanced, namely in Warren & Hewett (2002), so we now use the spectral cloning technique to bring real quasar spectral data to the problem; 1198 quasars from redshifts 2.3 ≤ z ≤ 3.32 were used for the cloning, and these were redshifted to the range 5.5 ≤ z ≤ 10.5. As with the riz and izJ samples around z ~ 5 and 6, these quasars were selected in order to ensure the presence of original spectral information in the final cloned quasars throughout the bands ZYJH—the filters of relevance to simulations up to z = 10.

The resulting color curves are shown in Figure 10. For comparison, the locations of the ZYJ filters are also shown, with both redshift and wavelength labels corresponding to the location of Ly\alpha.

5.2. Quasar Colors at z > 6.5

The behavior of the three ZYJH color curves is very similar—quasar color rises gradually as the Ly\alpha break passes through the band and increases rapidly as it leaves the tail of the filter. This rapid rise is thus the most sensitive regime of the color-redshift measurement. However, the three color curves presented in Figure 10 are an interesting departure from the curves of lower redshift quasars, in which small, but significant, flux could usually be relied on to be present below Ly\alpha. This minimal flux served
to ensure that even after the passage of the Lyα break through an entire band, model spectra would have some flux remaining in the blueward band and thus reasonably stable colors with increasing redshift, i.e., on the order of $m_1 - m_2 < 5$.

With quasars above $z = 6.5$, however, we encounter for the first time (in the sense of survey planning) an expected complete damping of the residual flux, which leads to the possibility—at least in modeled systems and synthetic spectra—of arbitrarily large colors. While we plot color values up to $m_1 - m_2 = 5$, in fact our simulations continue beyond this point to find values as high as 13 or 14, which are clearly not meaningful for observational purposes. Because a value of $m_1 - m_2 > 5$ is consistent with both Lyα only slightly redshifted beyond the blueward band and Lyα having been well redshifted out of the blueward band, it is more reasonable to rely on the next color for redshift estimation and treat the first color as a lower redshift limit. In two-color diagrams of this redshift range (Fig. 11), therefore, we remind the reader that the redshift track should be regarded as degenerate above $x$-values of 5.

Finally, a major barrier to the potential success of $ZYJH$ quasar color selection is the declining spatial density of objects with increasing redshift. In this respect the difficulty of finding $z > 6.5$ quasars is, of course, multiply compounded compared to that of $z \sim 6$—the quasars are expected to be rarer, fainter, and of higher color decrement, factors that all pose observational challenges. If we adopt the decreasing quasar spatial density evolution of Fan et al. (2004) and predict $M_{1450} < -26.7$ quasars at even higher redshifts, we find that in the range $6.5 \leq z \leq 7.5$, a total of only 90 such quasars are to be expected on the whole sky. Quasars of this brightness, if they exist at redshifts $z \sim 7$, will have moved into the $Y$ band and will be fainter by a half magnitude compared to the known objects at $z \sim 6$. The detection of $z \sim 7$ quasars will be a challenging endeavor indeed.

What choices will be faced in optimizing the likelihood of observing such rare, distant objects? Clearly, the trade-off between limiting magnitude and areal coverage is a significant concern for any large extragalactic survey. Ordinarily, if a quasar or galaxy survey seeks to maximize the number of objects observed, the decision whether to pursue deeper observations at the cost of survey area is dependent on the targeted objects’ luminosity function. Specifically, for example, surveying new area with incremental observing time is generally expected to yield new objects in proportion to the additional time spent, i.e., twice the area equals twice the objects. And in order for this additional time to be spent as effectively on deeper observations instead (where $S/N = t^{1/2}$), the objects of interest must obey a number density increase of at least $2^{\left[2.5 \log t/2\right]} = 6.3 \text{ mag}^{-1}$. However, in surveys for the highest redshift objects, which naturally seek the few most luminous objects first, depth is a necessary precursor to wide areas. At the bright tail of the luminosity function, where objects brighter than a certain absolute magnitude are effectively nonexistent, doubling the area will yield no objects if the survey is not deep enough. In such cases then, appropriately deep, moderate to smaller area observations seem to most effectively use finite telescope resources. Surveys such as UKIDSS, which will probe to limits of $Y = 20.5$, seem to offer hope for establishing the luminosity properties of these desired rare objects, in preparation for casting a broader area search.

6. CONCLUSION

Large-area sky surveys have often been motivated by the potential discovery of large numbers of objects that are just out of reach with present capabilities. The rapid advance in quasar information achieved in the past several years through such surveys has provided the foundation for extending the redshift frontier even farther, with digital libraries of quasars that can be used to predict new, even more distant populations. With a large number of quasars at low redshift, we have cloned and simulated
the diverse range of colors of potentially observable objects at $z > 6.5$, as well as shown how quasar cloning can improve the completeness estimates of sparse quasar samples at intermediate redshifts, such as $z \sim 5$ and 6.

The 10 quasars discovered at redshifts $4.73 < z < 5.30$ in this work illustrate how cloned quasar color simulations can aid in the search for faint objects and help build more robust statistics of sparse populations. We reached 0.7 mag deeper than the SDSS spectroscopic survey with this targeted search and project a 3 times greater quasar discovery rate for this depth increase; deeper co-adds of SDSS imaging (planned for release) therefore seem to offer excellent prospects for additional discoveries of faint, distant quasars.

As the focus of cosmological attention is increasingly shifted to longer wavelengths, observers will seek deeper and redder observations to probe the properties of early objects. Aside from the spectacular depth gains that can be achieved by a space-based infrared survey mission such as the Primordial Explorer (Zheng et al. 2002), UKIDSS and similar ground-based infrared surveys provide the best hope of glimpsing the $z \sim 7$ epoch of quasar activity. We hope the diversity of objects simulated in this work will provide a useful guide for the understanding and discovery of the next generation of quasars.

The authors thank P. Hewett and S. Warren for providing useful information regarding the UKIDSS filter system. This research was partially supported by NSF grant 03-07582 (D. P. S.).

K. G. acknowledges support from the David and Lucile Packard Foundation. Observations were carried out at the APO 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium (ARC); at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan; and at the HET, a joint project of the University of Texas at Austin, Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen. The HET is named in honor of its principal benefactors, William P. Hobby and Robert E. Eberly. We thank the telescope and instrument staffs at the Subaru Telescope and the APO for their expert assistance and knowledge during observations.

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the NSF, the US Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org/.

The SDSS is managed by the ARC for the Participating Institutions. The Participating Institutions are the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Korean Scientist Group, Los Alamos National Laboratory, the Max Planck Institute for Astronomy, the Max Planck Institute for Astrophysics, New Mexico State University, the University of Pittsburgh, the University of Portsmouth, Princeton University, the US Naval Observatory, and the University of Washington.

The authors thank P. Hewett and S. Warren for providing useful information regarding the UKIDSS filter system. This research was partially supported by NSF grant 03-07582 (D. P. S.).

K. G. acknowledges support from the David and Lucile Packard Foundation. Observations were carried out at the APO 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium (ARC); at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan; and at the HET, a joint project of the University of Texas at Austin, Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen. The HET is named in honor of its principal benefactors, William P. Hobby and Robert E. Eberly. We thank the telescope and instrument staffs at the Subaru Telescope and the APO for their expert assistance and knowledge during observations.

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the NSF, the US Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org/.

The SDSS is managed by the ARC for the Participating Institutions. The Participating Institutions are the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Korean Scientist Group, Los Alamos National Laboratory, the Max Planck Institute for Astronomy, the Max Planck Institute for Astrophysics, New Mexico State University, the University of Pittsburgh, the University of Portsmouth, Princeton University, the US Naval Observatory, and the University of Washington.

The authors thank P. Hewett and S. Warren for providing useful information regarding the UKIDSS filter system. This research was partially supported by NSF grant 03-07582 (D. P. S.).

K. G. acknowledges support from the David and Lucile Packard Foundation. Observations were carried out at the APO 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium (ARC); at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan; and at the HET, a joint project of the University of Texas at Austin, Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen. The HET is named in honor of its principal benefactors, William P. Hobby and Robert E. Eberly. We thank the telescope and instrument staffs at the Subaru Telescope and the APO for their expert assistance and knowledge during observations.

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the NSF, the US Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org/.

The SDSS is managed by the ARC for the Participating Institutions. The Participating Institutions are the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Korean Scientist Group, Los Alamos National Laboratory, the Max Planck Institute for Astronomy, the Max Planck Institute for Astrophysics, New Mexico State University, the University of Pittsburgh, the University of Portsmouth, Princeton University, the US Naval Observatory, and the University of Washington.

The authors thank P. Hewett and S. Warren for providing useful information regarding the UKIDSS filter system. This research was partially supported by NSF grant 03-07582 (D. P. S.).