Discovery of a Color-Selected Quasar at $z = 5.50$[1]

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ABSTRACT

We present observations of RD J030117+002025, a quasar at $z = 5.50$ discovered from deep, multi-color, ground-based observations covering 74 arcmin^2. This is the most distant quasar or AGN currently known. The object was targeted as an R-band dropout, with $R_{AB} > 26.3$ (3σ limit in a $3''$ diameter region), $I_{AB} = 23.8$, and $z_{AB} = 23.4$. The Keck/LRIS spectrum shows broad Lyα/N V λ1240 emission and sharp absorption decrements from the highly-redshifted hydrogen forests. The fractional continuum depression due to the Lyα forest is $D_A = 0.91$. RD J030117+002025 is the least luminous, high-redshift quasar known ($M_B \approx -22.7$).

Subject headings: quasars: general – quasars: individual (RD J030117+002025) – early universe

1. Introduction

The past few years have witnessed a watershed in our direct observations of the high-redshift Universe. A decade ago, only a handful of galaxies were identified past a redshift of 3. These sources represented the rare beast in the cosmos: high-redshift radio galaxies, or galaxies associated with extremely distant, luminous quasars. New techniques and instruments allow us now to routinely identify normal, star-forming galaxies at these same epochs (e.g., Steidel et al. 1996). Stern & Spinrad (1999) review modern search techniques for distant galaxies. Improved computing power and ambitious, large-area surveys also have pushed the frontier of distant quasar studies (e.g., Djorgovski et al. 1999; Fan et al. 1999). Now we are regularly identifying objects which have collapsed only ~ 1 Gyr after the Big Bang. Such observations tell us about the earliest phases of galaxy and structure formation and probe the conditions of the early Universe.

The identification of high-redshift quasars is especially important for several reasons. First, quasars at early cosmic epoch require the rapid formation of a supermassive black hole. Assuming black holes are not primordial, this requires the condensation of a large cloud of hydrogen, presumably embedded within a dark matter halo. Additionally, the presence of metal lines in quasars demand a previous generation of stars (two generations for nitrogen). High-redshift quasars thus constrain models of galaxy and structure formation (e.g., Loeb 1993; Eisenstein & Loeb 1995). Also, quasars provide valuable probes of the intervening intergalactic medium (e.g., Rauch 1998) and the intergalactic ionizing background. For example, the absence of a smooth depression in quasar continua short-ward of the Lyα emission strongly constrains the amount of neutral hydrogen in the intergalactic medium (Gunn & Peterson 1965). Songaila et al. (1999) find no Gunn-Peterson trough out to redshift 5 from deep spectroscopic observations of SDSSp J033829.31+002156.3 at $z = 5.00$ (Fan et al. 1999).

In this Letter, we report the discovery of a quasar at $z = 5.50$, the most distant quasar identified to date. The previous most distant quasar was SDSSp J120441.73−002149.6 at $z = 5.03$ (Fan et al. 2000). At $z = 5.50$, an $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}, \Lambda = 0, \Omega = 1$ (0.1) universe is 790 Myr (1.51 Gyr) old, corresponding to a look-back time of 94.0% (90.9%) of the age of the universe. For the

lambda cosmology supported by recent studies of distant supernovae, $H_0 = 65 \, \mathrm{km \, s^{-1} \, Mpc^{-1}}, \Lambda = 0.7, \Omega_\mathrm{m} = 0.3$, the universe is 1.11 Gyr old at $z = 5.50$, corresponding to a look-back time of 92.4% of the age of the universe.

2. Observations and Target Selection

RD J030117+002025 was identified from deep RIz-band imaging using a slightly redder version of the 'dropout' color selection techniques which have proved successful at identifying high-redshift galaxies (e.g., Steidel et al. 1996; Dey et al. 1998; Spinrad et al. 1998) and quasars (e.g., Kennefick, Djorgovski, & de Calvalho 1995; Djorgovski et al. 1999; Fan et al. 1999; Stern et al. 2000b). The selection criteria rely upon absorption from the Lyα and Lyβ forests attenuating the rest-frame ultraviolet continua. At $z \simeq 5$, such objects will disappear from the R-band. Long-ward of the redshifted Lyα, both quasars and star-forming galaxies display relatively flat (in f_ν) continua. In concept, our survey is similar to established quasar surveys relying upon the digitized Palomar Sky Survey (e.g., Djorgovski et al. 1999) or Sloan Digital Sky Survey (e.g., Fan et al. 1999). In practice, we probe a much smaller area of sky (eventually a few $\times$ 100 arcmin^2) to much fainter magnitudes. Our survey is designed to study the high-redshift, "normal" galaxy population, but is also sensitive to (low-luminosity) high-redshift quasars.

The Iz imaging was obtained using the Kitt Peak National Observatory 150″ Mayall telescope with its Prime Focus CCD imager (PFCCD) equipped with a thinned AR coated 2048 $\times$ 2048 Tektronics CCD. This configuration gives a 14.3 $\times$ 14.3 arcminute field of view with 0″43 pixels. The CCD was operated using "short scan", where the CCD was mechanically displaced while its charge is shifted in the opposite direction to reduce fringing at I and z to very low levels. Two hours of I-band data were obtained on UT 1995 August 31. The z-band data were obtained during UT 1997 November 4 – 6, and the summed image represents 3.3 hours of integration. The combined, processed I and z images reach limiting magnitudes of 25.7 and 24.8 mag, respectively (3σ limits in 3″ diameter apertures; AB magnitudes are used throughout this Letter) and have 0″9 and 1″2 seeing, respectively. These images comprise one field in the $BRIzJK$ Elston, Eisenhardt,

& Stanford (2000) field galaxy survey.

On UT 1999 November 11 − 12, we used the COSMIC camera (Kells et al. 1998) on the 200″ Hale telescope at Palomar Observatory to obtain extremely deep (4.4 hour) R-band imaging of the same field, with the purpose of identifying high-redshift candidates. COSMIC uses a 2048 × 2048 pixel SITe (formerly Tektronix) thinned CCD with 0″2846 pixels, yielding a 9.7 × 9.7 arcmin field-of-view. Our combined, processed R-band image has 1″2 seeing and reaches a depth of 26.3 mag (3σ limit in 3″ diameter aperture).

High-redshift candidates for spectroscopy, designated RD for R-drop, were identified on the basis of a strong $R − I$ color index and relatively flat $I − z$ color. No morphological criteria were implemented as the primary goal of this program is to study "normal," star-forming galaxies at high redshift. Candidates were then screened by eye, yielding a total of six good targets over the central 74 arcmin^2 field. Fig. 1 presents a finding chart for RD J030117+002025, the brightest of our candidates and the subject of this Letter. Other candidates will be discussed in a future publication.

We obtained spectra of several R-band dropouts through 1″5 wide, 13″ − 44″ long slitlets using the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck II telescope on UT 2000 January 10 and 11. Observations were obtained at a position angle of −111.6° (east of north) with the 150 lines mm^{-1} grating ($\lambda_{\text{blaze}} = 7500$ Å; $\Delta\lambda_{\text{FWHM}} \approx 17$ Å). The spectra sample the wavelength range 4000 Å to 1μm. Seeing was $\approx 1″1$ during both nights and conditions were photometric. We performed $\approx 3″$ spatial offsets between each 1800 s exposure in order to facilitate removal of fringing at long wavelength ($\lambda \gtrsim 7200$ Å).

All data reductions were performed using IRAF and followed standard slit spectroscopy procedures. We calculated the dispersion using a HgNeArKr lamp spectrum observed immediately subsequent to the science observations (RMS variations of 0.6 Å), and employed telluric emission lines to adjust the wavelength zero-point. The spectra were flux-calibrated using observations of Feige 67 and Feige 110 (Massey & Gronwall 1990). We corrected for foreground Galactic extinction using a reddening of $E_{\text{B−V}} = 0.03$ determined from the dust maps of Schlegel, Finkbeiner, &

Davis (1998). The final composite spectrum of RD J030117+002025, presented in Fig. 2, represents 4.5 hours of integration.

3. Results and Discussion

Though of moderate signal-to-noise ratio, the spectrum of RD J030117+002025 has the unambiguous signature of an extremely distant quasar. The broad emission with a sharp absorption at 7900 Å is consistent with Lyα/N V λ1240 emission attenuated by the nearly opaque Lyα forest at $z = 5.50$. An additional discontinuity is visible at 6690 Å, associated with the Lyβ forest. The Lyα forest absorption and poor detection of the long-wavelength Si IV/O IV] λ1403 emission make centroiding on the emission features ill-advised; the redshift is instead determined from the sharp forest decrements. We estimate $z = 5.50 \pm 0.02$. This and other properties of RD J030117+002025 are given in Table 1.

The spectral character of RD J030117+002025 is slightly atypical of high-redshift quasars, though it undoubtedly resides within the diverse category of quasars. The Lyα/N V complex is unusually broad and distinguishing the emission lines is impractical. Many of the highest redshift quasars share similar spectroscopic shapes, e.g., SDSSp J033829.31+002156.3 at $z = 5.00$, SDSSp J021102.72−000910.3 at $z = 4.90$ (Fan et al. 1999), and GB 1428+4217 at $z = 4.72$ (Hook & McMahon 1998).

The strong continuum absorption associated with the Lyα forest is the dominant spectroscopic feature of RD J030117+002025. A robust determination of D_A, the standard parameter for describing the Lyα forest decrement (Oke & Koryanski 1982), requires knowledge of the continuum spectral slope long-ward of Lyα. We estimate D_A by assuming the standard quasar power law spectral index of -0.5 for the continuum long-ward of Lyα (e.g., Richstone & Schmidt 1980; Schneider et al. 1992), with the amplitude determined over the wavelength interval $\lambda\lambda8400 - 9000$ Å (between the N V λ1240 and Si IV/O IV] λ1403 emission complexes). We derive $D_A = 0.91$. For $f_\nu \propto \nu^0$, this value does not change significantly. The value is comparable to those measured for distant

galaxies in the Hubble Deep Field at similar redshifts (Weymann et al. 1998; Spinrad et al. 1998) and models of the Lyα forest (Madau 1995; Zhang et al. 1997).

At $z = 5.50$, the features used to describe continuum properties are redshifted to challenging wavelengths. We estimate $AB_{1450(1+z)}$ using the continuum modeled above. Consistent with previous work in this field, M_B is calculated for an Einstein-de Sitter universe with $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}, q_0 = 0.5$ and the standard quasar power law index of -0.5. We find $M_B \approx -22.7$; see Stern et al. (2000a) for details of how we calculate M_B.

Comparison with the 1.4 GHz FIRST survey (Becker, White, & Helfand 1995) reveals no radio source within $30''$ of the quasar to a limiting flux density of $f_{1.4\mathrm{GHz}} \simeq 1$ mJy (5σ).

How unusual is it to find a quasar as distant and luminous as RD J030117+002025 in a $\simeq 100$ arcmin^2 field? This is difficult to answer as RD J030117+002025 is the least luminous $z > 4$ quasar known. The previously known high-redshift $(z > 4)$ quasars of lowest luminosity are PC 0027+0521 $(z = 4.21, M_B = -24.0$; Schneider, Schmidt, & Gunn 1994), which was discovered serendipitously, and the X-ray selected quasar RX J105225.9+571905 $(z = 4.45, M_B = -23.9$; Schneider et al. 1998). These luminosities are comparable to the lower luminosity objects in the $z \lesssim 1$ Bright Quasar Survey (Schmidt & Green 1983). Most high-redshift quasar luminosity functions (e.g., Schmidt, Schneider, & Gunn 1995) have been derived from samples of quasars ≈ 100 times as luminous as RD J030117+002025. To calculate the expected surface density of high-redshift, faint quasars, we instead follow the methodology outlined in Kennefick et al. (1995) and Boyle & Terlevich (1998): we adopt the Boyle et al. (1991) $z = 2$ quasar luminosity function (for $q_0 = 0.5$), scaled down in density using the evolution predicted by Schmidt et al. (1995), namely, that the quasar space density falls off by a factor of 2.7 per unit redshift beyond $z = 3$. The predicted surface density of R-drop $(4.3 \lesssim z \lesssim 5.8)$ quasars with $M_B \leq -22.5$ is $\simeq 2 \times 10^{-3}$ arcmin^{-2}, implying ≈ 0.15 such quasars should have been uncovered in our survey.

It is dangerous, yet enticing, to draw conclusions from a single object. The discovery of the quasar RD J030117+002025 at $z = 5.50$ in the modest sky coverage of our survey is suggestive of less dramatic evolution in the quasar luminosity function at faint magnitudes and high redshift.

Such a change would have significant cosmological implications, including changing the budget of high-energy, ionizing photons in the early Universe. We also note that the low signal-to-noise ratio data are suggestive of strong hydrogen absorption near the quasar redshift. Is this due to a neutral hydrogen cloud near the quasar, at odds with the inverse proximity effect? Or are we seeing the first glimpses of an object radiating prior to the reionization epoch, with neutral intergalactic hydrogen absorbing the rest-frame UV photons? Higher resolution, higher signal-to-noise ratio data will be essential for answering these questions.

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Fig. 1.— Finding chart for RD J030117+002025, a quasar at $z = 5.50$, from the KPNO I-band imaging. The field is $2' \times 2'$, centered at $\alpha = 03^{\mathrm{h}}01^{\mathrm{m}}17.01^{\mathrm{s}}, \delta = +00°20'25''96$ (J2000). North is at the top and east is to the left. The quasar is unresolved in this $0''9$ seeing image.

Fig. 2.— Spectrum of RD J030117+002025 at $z = 5.50$, obtained with LRIS on the Keck II telescope. The total exposure time is 4.5 hours, and the spectrum was extracted using a $1''5 \times 1''5$ aperture. The spectrum has been smoothed using a 15 Å boxcar filter. Vertical dotted lines indicate the expected wavelength of common spectroscopic features in quasars; not all are detected.

Table 1.   Properties of RD J030117+002025

Parameter	Value	Parameter	Value
α (J2000)	$03^{\mathrm{h}}01^{\mathrm{m}}17.01^{\mathrm{s}}$	z	5.50 ± 0.02
δ (J2000)	$+00°20'25''96$	$AB_{1450(1+z)}$ (mag)	24.1
R_{AB} (mag)	> 26.3	M_B (mag)	-22.7
I_{AB} (mag)	23.8	$W^{\mathrm{obs}}_{\mathrm{Ly}\alpha/\mathrm{NV}}$ (Å)	$\simeq 300$
z_{AB} (mag)	23.4	D_A	0.91

Note. — R-band magnitude is 3σ limit is a $3''$ diameter aperture.