

To appear in *P. A. S. P.***The Low Resolution Spectrograph of the Hobby-Eberly Telescope II.****Observations of Quasar Candidates from the Sloan Digital Sky Survey ^{1,2}**

D.P. Schneider³, Gary J. Hill⁴, X. Fan⁵, L.W. Ramsey³, P.J. MacQueen⁴, D.W. Weedman³, J.A. Booth⁴, M. Eracleous³, J.E. Gunn⁵, R.H. Lupton⁵, M.T. Adams⁴, S. Bastian⁶, R. Bender⁷, E. Berman⁶, J. Brinkmann⁸, I. Csabai^{9,10}, G. Federwitz⁶, V. Gurbani⁶, G.S. Hennessy¹¹, G.M. Hill⁴, R.B. Hindsley¹¹, Z. Ivezić⁵, G.R. Knapp⁵, D.Q. Lamb¹⁴, C. Lindenmeyer⁶, P. Mantsch⁶, C. Nance⁴, T. Nash⁶, J.R. Pier¹², R. Rechenmacher⁶, B. Rhoads⁴, C.H. Rivetta⁶, E.L. Robinson⁴, B. Roman⁴, G. Sergey⁶, M. Shetrone⁴, C. Stoughton⁶, M.A. Strauss⁵, G.P. Szokoly⁶, D.L. Tucker⁶, G. Wesley⁴, J. Willick¹³, P. Worthington⁴, and D.G. York¹⁴

email addresses: dps@astro.psu.edu, hill@bento.as.utexas.edu, fan@astro.princeton.edu

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²Based on observations obtained with the Hobby-Eberly Telescope, which is a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen.

³Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802.

⁴Department of Astronomy, McDonald Observatory, University of Texas, Austin, TX 78712.

⁵Princeton University Observatory, Princeton, NJ 08544.

⁶Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510.

⁷Universitäts-Sternwarte, Scheinerstrasse 1, 81679 München, Germany.

⁸Apache Point Observatory, P.O. Box 59, Sunspot, NM 88349-0059.

⁹Department of Physics and Astronomy, Johns Hopkins University, 3701 University Drive, Baltimore, MD 21218.

¹⁰Department of Physics of Complex Systems, Eötvös University, Pázmáy Péter sétány 1/A, H-1117, Budapest, Hungary.

¹¹US Naval Observatory, 3450 Massachusetts Avenue NW, Washington, DC 20392-5420.

¹²US Naval Observatory, Flagstaff Station, P.O. Box 1149, Flagstaff, AZ 86002-1149.

¹³Department of Physics, Stanford University, Stanford, CA 94305.

¹⁴Astronomy and Astrophysics Center, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637.

ABSTRACT

This paper describes spectra of quasar candidates acquired during the commissioning phase of the Low-Resolution Spectrograph of the Hobby-Eberly Telescope. The objects were identified as possible quasars from multicolor image data from the Sloan Digital Sky Survey. The ten sources had typical r' magnitudes of 19–20, except for one extremely red object with r' of ≈ 23 . The data, obtained with exposure times between 10 and 25 minutes, reveal that the spectra of four candidates are essentially featureless and are not quasars, five are quasars with redshifts between 2.92 and 4.15 (including one Broad Absorption Line quasar), and the red source is a very late M star or early L dwarf.

Subject headings: instrumentation: spectrographs — quasars: general — stars: low-mass, brown dwarfs

1. Introduction

The Hobby-Eberly Telescope (HET), located at McDonald Observatory in west Texas, is the first optical/IR 8-m class telescope to employ a fixed altitude (Arecibo-type) design (Ramsey, Sebring, and Sneden 1994; Hill 1995; Ramsey et al. 1998). The spherical primary, consisting of 91 identical hexagonal mirrors, is 11.1 m across and is oriented 35° from the zenith; full azimuth motion allows access to all declinations between -10° and $+72^\circ$. During an observation the azimuth of the telescope is fixed and objects are followed by a tracker assembly located 13.08 m above the primary, riding at the top of the telescope structure (Booth, Ray, and Porter 1998). The tracker carries a four-mirror corrector which delivers a $4'$ diameter field of view, and can follow an object continuously for between 40 minutes and 2.5 hours, depending on the source declination. Only for a fraction of this time, however, does the 9.2-m diameter entrance pupil fall entirely on the primary mirror; the minimum equivalent aperture at the track extremes is 6.8-m, and the average equivalent aperture for a “typical” observation is approximately 8-m.

Groundbreaking for the HET occurred in March 1994, and the telescope was dedicated on 8 October 1997. The first HET facility instrument, the Marcario Low Resolution Spectrograph (LRS; Hill et al. 1998a,b, 2000a; Cobos et al. 1998) was installed in the tracker in April 1999. Commissioning of the LRS took place during the dark time in April, May, and June 1999; this paper, along with Hill et al. (2000b), presents initial science results from these observations.

Spectra of ten high-redshift quasar candidates from the Sloan Digital Sky Survey (SDSS; Gunn and Weinberg 1995, SDSS Collaboration 1996, York et al. 1999) were obtained with the LRS during the Spring 1999 campaign. The results demonstrated that although the image quality of the HET primary had yet not reached design specifications, ten-minute exposures of $r' \approx 19$ –20 quasars were

adequate to measure redshifts, and a twenty-five minute exposure of an $r' \approx 23$, $i' \approx 20.4$ L dwarf yielded an accurate stellar classification.

2. Observations

2.1. Sloan Digital Sky Survey

The SDSS is using a CCD camera (Gunn et al. 1998) on a dedicated 2.5-m telescope (Siegmund et al. 1999) at Apache Point Observatory, New Mexico, to obtain images in five broad optical bands over 10,000 deg² of the high Galactic latitude sky centered approximately on the North Galactic Pole. The five filters (designated u' , g' , r' , i' , and z') cover the entire wavelength range of the CCD response (Fukugita et al. 1996). Photometric calibration is provided by simultaneous observations with a 20-inch telescope at the same site. The survey data processing software provides the astrometric and photometric calibrations, as well as identification and characterization of objects (Pier et al. 1999, Lupton et al. 1999b).

The high photometric accuracy of the SDSS images and the information provided by the z' filter (central wavelength of 9130 Å) makes the SDSS data an excellent source for identification of high-redshift quasar candidates. If the redshift of a quasar exceeds ≈ 3.5 , the combination of the strong Ly α line (typical observed equivalent width of 400 Å) and absorption produced by intervening neutral hydrogen (at $z = 4$ approximately half of the radiation shortward of the Ly α emission line is absorbed) causes the optical colors of high-redshift quasars to radically deviate (often by more than a magnitude; see Fan 1999, Fan et al. 1999) from the colors of stars.

Fan et al. (1999) were able to identify 15 new quasars at redshifts larger than 3.65 (including four with $z > 4.5$) from early SDSS commissioning data; recent work (Fan et al. 2000a) has increased the number of SDSS high-redshift quasars to over 35. During the course of these investigations, observations of a number of quasar candidates have revealed a significant number of objects cooler than M-type stars (Fan et al. 2000b), including the identification of the first field methane dwarf (Strauss et al. 1999).

Quasar candidates were selected, using the multicolor technique similar to that of Fan et al. (1999a), from point sources in two equatorial SDSS strips taken in March 1999. Both low ($z < 3.5$, from the “ $u^*g^*r^*$ ” diagrams) and high ($z > 3.5$, from the “ $g^*r^*i^*$ ” and “ $r^*i^*z^*$ ” diagrams) redshift quasar candidates were chosen. Since the photometric measurements of this commissioning data have not yet been placed on the final SDSS system, we use the symbols u^* , g^* , r^* , i^* , and z^* to indicate that the photometry is similar but not identical to the final SDSS photometric system.

2.2. Spectroscopy of Quasar Candidates

Spectra of ten of the SDSS quasar candidates were obtained with the LRS between April and June 1999. Details of the optical and mechanical design and the performance of the LRS are provided in the companion paper (Hill et al. 2000a); below is a brief description of the instrument as employed for the present observations.

The LRS is mounted in the Prime Focus Instrument Package, which rides on the HET tracker. The image scale is $4.89'' \text{ mm}^{-1}$ at the entrance aperture to the LRS; the observations of SDSS objects were taken with long slits with widths of $2''$ or $3''$. The dispersive element was a 300 line mm^{-1} grism blazed at 5500 \AA . The detector is a thinned, antireflection-coated 3072×1024 Ford Aerospace CCD. The pixel size is $15 \mu\text{m}$; the scale on the detector is $0.25'' \text{ pixel}^{-1}$. The CCD has a gain of $2.5 e^- \text{ ADU}^{-1}$ and a read noise of approximately $7 e^-$. The CCD was binned 2×2 during read-out of the SDSS observations; this produced a data frame size of 1568×512 and an image scale of $0.50'' \text{ pixel}^{-1}$.

LRS wavelength calibration was provided by Ne, Cd, and Ar comparison lamps. The wavelength calibration between $4400\text{--}10,700 \text{ \AA}$ is well fit (rms residuals of about a tenth of a pixel) by a fourth-order polynomial. The dispersion ranges from $4.00 \text{ \AA pixel}^{-1}$ at the blue end to $4.76 \text{ \AA pixel}^{-1}$ in the near infrared. The resolution with the $2''$ slit is 20 \AA ($R = 300$ at 6000 \AA).

The observing conditions varied from nearly photometric to scattered cloud cover. Typically 86 of the 91 segments of the primary were in operation during the data acquisition, and the image quality ranged from $1.6''$ (FWHM) to over $5''$. The exposure time per object ranged from 10 to 25 minutes. The relative flux calibration was provided by observations of spectrophotometric standards, usually those of Oke and Gunn (1983). Absolute spectrophotometric calibration was carried out by scaling each spectrum so that i^* magnitudes synthesized from the spectra matched the SDSS photometric measurements.

Six of the ten SDSS quasar candidates had interesting spectra; finding charts are given in Figure 1. The official names for the sources are SDSSp Jhhmmss.ss+ddmmss.s, where the coordinate equinox is J2000. For brevity, the objects will be referred to as simply SDSS hhmm+dd throughout most of this paper. The spectra of the remaining four objects were basically featureless; given the signal-to-noise ratio of these four spectra, one can state that they are not quasars or late-type stars.

The spectra from $4500\text{--}9200 \text{ \AA}$ for the six sources are displayed in Figure 2 (The data have been binned so that there are approximately two pixels per resolution element). The data for all objects were taken through the $2''$ slit except for the spectrum of SDSS 1624–00 ($3''$ slit); the spectrum of SDSS 1405–00 was acquired with an OG515 blocking filter.

Prominent spectral features are labelled in the figure. Four of the sources are definitely quasars with redshifts between 2.92 and 4.15 (also see Fan et al. 2000a for observations of SDSS 1310-00 and SDSS 1447–00), one (SDSS 1347+00) is probably a quasar at $z \approx 3.8$, and one (SDSS 1430+00) is a very cool star or substellar object.

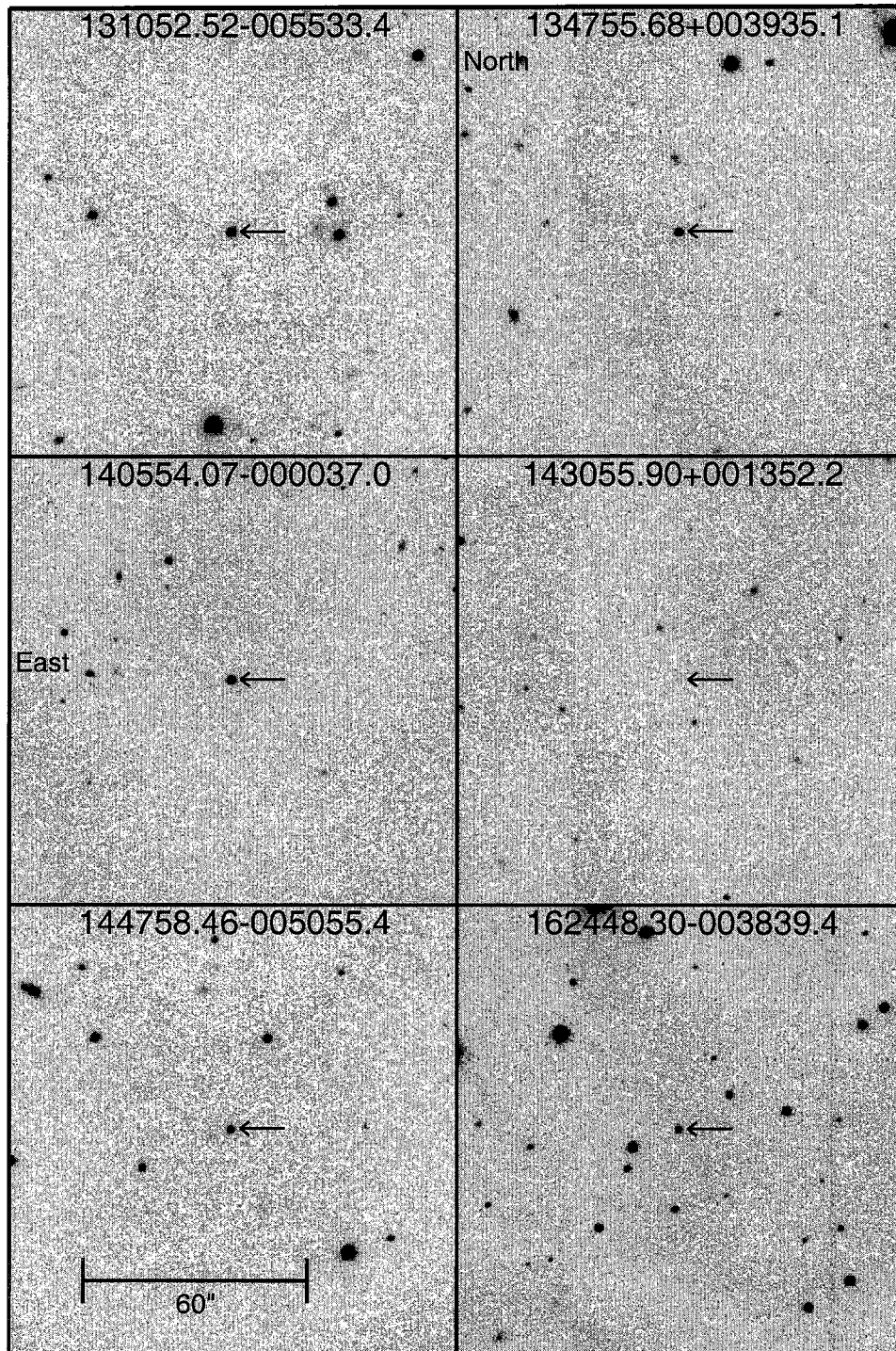


Fig. 1.— Finding charts for the six objects; the data were taken with the SDSS imaging camera in the r' filter. The orientation of the charts is north at the top and east to the left. Each chart is $120''$ on a side.

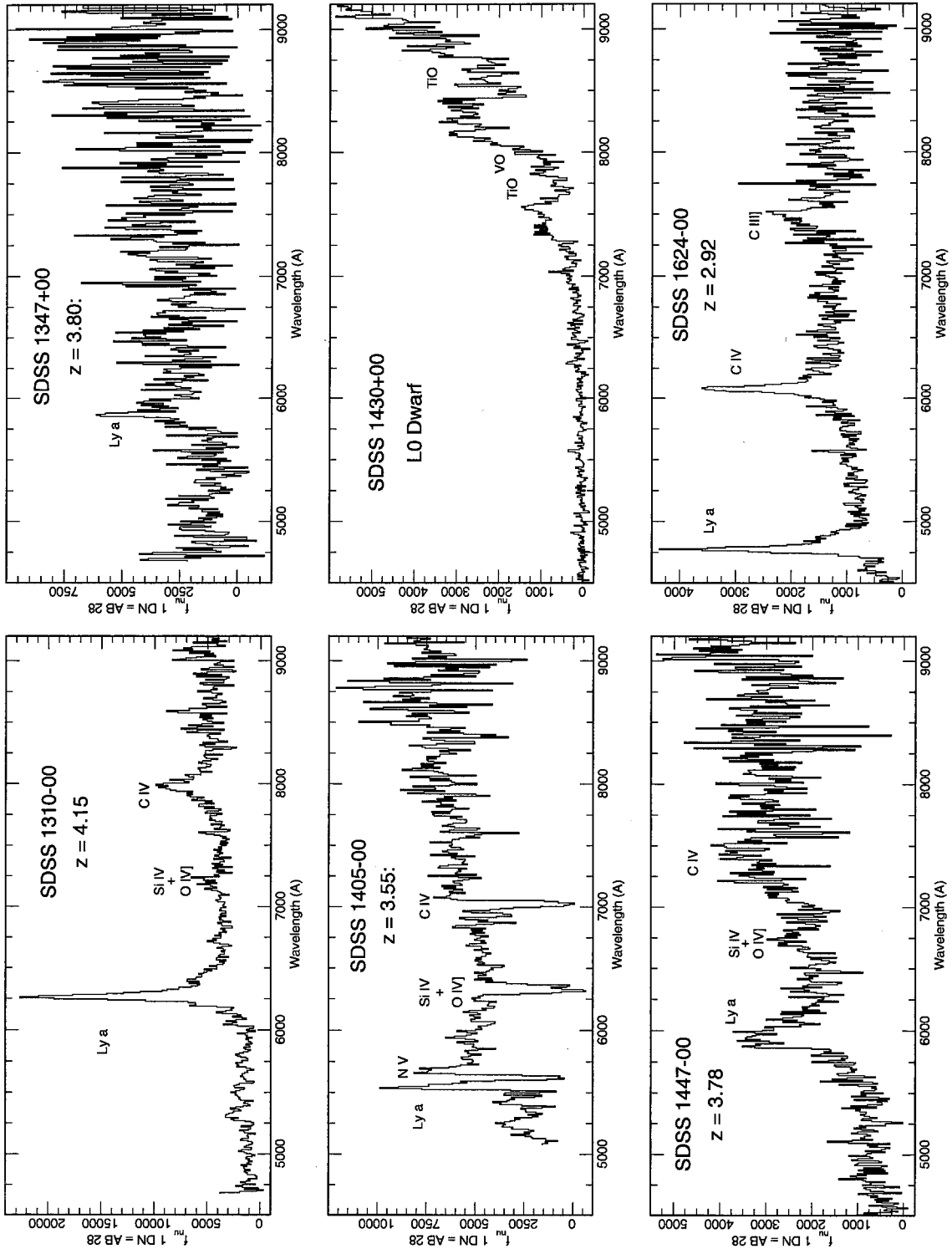


Fig. 2.— Spectra of the SDSS objects taken with the Low-Resolution Spectrograph on the Hobby-Eberly Telescope. Exposure times ranged from 600 s to 1465 s. The spectral resolution is 20 Å except for 1624–00, where the resolution is 30 Å. The unit of flux is AB = 28.0 or 5.75×10^{-30} erg cm $^{-2}$ s $^{-1}$ Hz $^{-1}$.

3. Discussion

A summary of the observations of the six SDSS sources are given in Table 1. The table contains the object name, photometry with $1\text{-}\sigma$ errors from the SDSS data, UT date and exposure time of LRS observation, and the redshift of the source.

The photometry in Table 1 is quoted in asinh magnitudes (Lupton, Gunn, and Szalay 1999a) that are based on the *AB* system of Oke and Gunn (1983). Asinh magnitudes are essentially identical to the standard definition of magnitudes when the flux levels are well above zero; at low signal-to-noise ratio asinh magnitudes are linear in flux and do not diverge at zero (or negative) flux. The zero flux levels for the u^* , g^* , r^* , i^* , z^* bands were set to 24.24, 24.91, 24.53, 23.89, and 22.47, respectively, for the SDSS data reported here. For example, the g^* magnitude for 1420+00 (24.94) indicates that a small negative flux was measured in this band.

Redshift determinations for three of the quasars (SDSS 1310-00, SDSS 1447-00, and SDSS 1624-00) were quite straightforward; emission lines other than the absorption-affected Ly α line could be used for this measurement. The quasar SDSS 1405-00 is a strong Broad Absorption Line (BAL) with absorption from Ly α , N V, Si IV+O IV], and C IV. The BAL features have widths of approximately 3000 km s^{-1} and have a redshift of ≈ 3.53 ; we have assigned an approximate redshift of 3.55 to the quasar. The spectrum of SDSS 1347+00, with its prominent emission line at 5900 \AA and continuum drop across the line, is very suggestive of a redshift ≈ 3.8 object, but clearly a higher signal-to-noise ratio spectrum of the source is required for a definitive answer.

Some basic properties of the five quasars are given in Table 2: object name, redshift, color excess along line-of-sight (from Schlegel, Finkbeiner, and Davis 1998), the Galactic extinction corrected *AB* magnitude at 1450 \AA in the rest frame of the quasar, and the absolute *B* magnitude (assuming $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$, and the continuum between 1450 \AA and 4400 \AA in the quasar rest frame is a power law with an index of -0.5). In this cosmology 3C 273 has $M_B = -27.0$.

The remaining object, SDSS 1430+00, is clearly a very late-type dwarf; based on the classification scheme of Kirkpatrick et al. (1999), we classify the object as either late M or early L, with a best estimate of L0 (also see Fan et al. 2000b).

The results presented in this paper demonstrate that the HET/LRS can acquire, track, and obtain spectra of ≈ 20 th magnitude objects. The commissioning tests demonstrate that exposure times of the order of ten minutes produce data of sufficient signal-to-noise ratio to determine quasar redshifts and classify substellar objects at this brightness level. The LRS will begin normal operations in Fall 1999; the observations presented here are representative of the type of survey work that the LRS plans to undertake in the future.

The Sloan Digital Sky Survey (SDSS) is a joint project of the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, the Johns Hopkins University, the Max-Planck-Institute for Astronomy, Princeton University, the United States Naval Observa-

TABLE 1. SDSS Objects Observed with the HET^a

Object ^b	u^*	g^*	r^*	i^*	z^*	Date (1999)	Exp (s)	z
SDSSp J131052.52-005533.4	23.54 ±0.51	20.87 ±0.03	18.84 ±0.01	18.79 ±0.02	18.86 ±0.05	12 Jun	600	4.15
SDSSp J134755.68+003935.1	24.11 ±0.19	20.54 ±0.02	19.42 ±0.01	19.31 ±0.02	19.35 ±0.05	12 Jun	600	3.80
SDSSp J140554.07-000037.0	24.10 ±0.38	20.16 ±0.02	18.81 ±0.01	18.54 ±0.01	18.34 ±0.03	17 May	600	3.55
SDSSp J143055.90+001352.2	24.14 ±0.36	24.94 ±0.62	22.95 ±0.26	20.43 ±0.04	18.61 ±0.04	19 May	1465	0.00
SDSSp J144758.46-005055.4	23.95 ±0.18	21.04 ±0.03	19.57 ±0.02	19.35 ±0.02	19.15 ±0.05	18 May	600	3.78
SDSSp J162448.30-003839.4	22.12 ±0.12	20.36 ±0.02	20.09 ±0.02	20.15 ±0.02	20.04 ±0.03	23 Apr	1200	2.92

^a Photometry is reported in terms of asinh magnitudes; see text and Lupton, Gunn, and Szalay (1999a) for details. ^b Coordinate equinox is J2000.

TABLE 2. Properties of SDSS Quasars

Object	z	$E(B - V)$	AB_{1450}	M_B^a
SDSSp J131052.52-005533.4	4.15 ± 0.01	0.025	18.98	-27.4
SDSSp J134755.68+003935.1	3.80 ± 0.04	0.030	19.56	-26.7
SDSSp J140554.07-000037.0	3.55 ± 0.03	0.044	18.70	-27.4
SDSSp J144758.46-005055.4	3.78 ± 0.03	0.046	19.50	-26.8
SDSSp J162448.30-003839.4	2.92 ± 0.01	0.092	20.28	-25.6

^a Calculated assuming $H_0 = 50$, $q_0 = 0.5$, and $\alpha = -0.5$.

tory, and the University of Washington. Apache Point Observatory, site of the SDSS, is operated by the Astrophysical Research Consortium. Funding for the project has been provided by the Alfred P. Sloan Foundation, the SDSS member institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, and the Ministry of Education of Japan. The SDSS Web site is <http://www.sdss.org/>.

The Hobby-Eberly Telescope (HET) is a joint project of the University of Texas at Austin, the 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. The Marcario LRS was constructed by the University of Texas at Austin, Stanford University, Ludwig Maximilians-Universität München, the Instituto de Astronomia de la Universidad Nacional Autonomia de Mexico, Georg-August-Universitaet Goettingen, and Pennsylvania State University. The LRS is named for Mike Marcario of High Lonesome Optics who fabricated several optics for the instrument but died before its completion. This work was supported in part by National Science Foundation grants AST95-09919 and AST99-00703 (DPS), and AST96-18503 (MAS). MAS and XF acknowledge additional support from Research Corporation, the Princeton University Research Board, and an Advisory Council Scholarship.

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