The Sloan Digital Sky Survey: Technical Summary

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ABSTRACT

This paper summarizes the observational parameters and data products of the Sloan Digital Sky Survey (SDSS), and serves as an introduction to extensive technical on-line documentation. The goal of the SDSS is to provide the data to support detailed investigations of the distribution of luminous and non-luminous matter in the Universe: a photometrically and astrometrically calibrated digital imaging survey of π steradians above about Galactic latitude $30°$ in five broad optical bands to a depth of $g' \sim 23^m$, and a spectroscopic survey of the approximately 10^6 brightest galaxies and 10^5 brightest quasars found in the photometric object catalog produced by the imaging survey.

Subject headings:

1. Introduction

At this writing (Spring 2000) the Sloan Digital Sky Survey (SDSS) is nearing the end of its commissioning phase. The purpose of this paper is to provide a concise summary of the vital statistics of the project, a definition of some of the terms used in the survey and, via links to documentation in electronic form, access to detailed descriptions of the project's design, hardware, and software, to serve as technical background for the

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project's science papers. The electronic material is extracted from the text (the "Project Book") written to support major funding proposals and is available at the *Astronomical Journal* web site via the on-line version of this paper. The official SDSS web site (http://www.sdss.org) also provides links to the on-line Project Book, and it can be accessed directly at http://www.astro.princeton.edu/PBOOK/welcome.htm. In the discussion below we reference the chapters in the Project Book by the last part of the URL, i.e. that following PBOOK/. The versions accessible at the SDSS web sites also contain extensive discussions and summaries of the scientific goals of the survey, which are not included here.

The text of the on-line Project Book was last updated in August 1997. While there have been a number of changes in the hardware and software described therein, the material accurately describes the design goals and the implementation of the major observing subsystems. As the project becomes operational, we will provide a series of formal technical papers (most still in preparation), which will describe in detail the project hardware and software in its actual operational state. The overall project, including history, management, science drivers and summaries of all subsystems, will be described by York et al. (2000).

Section 2 describes the Survey's parameters: the imaging depth, sky coverage, and instrumentation. Section 3 summarizes the software and data reduction components of the SDSS, and its data products. Section 4 reviews some recent scientific results from the project's initial commissioning data runs, which demonstrate the ability of the project to reach its technical goals. All Celestial coordinates are in epoch J2000.

2. Survey Characteristics

The Sloan Digital Sky Survey will produce both imaging and spectroscopic surveys over a large area of the sky. The survey uses a dedicated 2.5 m telescope equipped with a large format mosaic CCD camera to image the sky in five bands, and two digital spectrographs to observe the spectra of about one million galaxies and 100,000 quasars selected from the imaging data.

The SDSS calibrates its photometry via observations of a network of standard stars established by the USNO 1 m telescope, and its astrometry via observations by an array of astrometric CCDs in the imaging camera.

2.1. Telescope

The SDSS telescope is a 2.5m f/5 modified Ritchey-Chrétien wide-field altitude-azimuth telescope (see `telescop/telescop.htm`; Siegmund et al. 2000) located at the Apache Point Observatory (APO), Sunspot, New Mexico (`site/site.htm`). The telescope achieves a very wide (3°) distortion-free field by the use of a complex large secondary mirror and two corrector lenses. It is equipped with the photometric/astrometric mosaic camera (`camera/camera.htm`, Gunn et al. 1998) and images the sky by scanning along great circles at the sidereal rate. The imaging camera mounts at the Cassegrain focus. The telescope is also equipped with two double fiber-fed spectrographs, permanently mounted at the back of the telescope. The telescope is changed from imaging mode to spectroscopic mode by removing the imaging camera and mounting at the Cassegrain focus a fiber plug plate, individually drilled for each field, which feeds the spectrographs. In survey operations, it is expected that up to nine spectroscopic plates per night will be observed, with the necessary plates being readied during the day. The telescope mounting and enclosure allow easy access for rapid changes between fiber plug plates and between spectroscopic and imaging modes. This strategy allows imaging to be done in pristine observing conditions (photometric conditions, seeing $\leq 1.2''$) and spectroscopy to be done during less ideal conditions. It also allows the use of partial nights, since all observing will be done in dark sky.

Besides the 2.5m telescope, the SDSS makes use of three subsidiary instruments at the site. The *Photometric Telescope* (PT) is a 0.5m telescope equipped with a CCD camera and the SDSS filter set whose task is to calibrate the photometry. Two instruments, a *seeing monitor* and a $10\mu m$ *cloud scanner* (Hull et al. 1995; `site/site.htm`) monitor the astronomical weather.

2.2. Camera

The SDSS camera contains two sets of CCD arrays: the imaging array and the astrometric arrays (`camera/camera.htm`, Gunn et al. 1998).

The *imaging array* consists of 30 2048 x 2048 Tektronix CCDs, placed in an array of six columns and five rows. The telescope scanning is aligned with the columns. Each row observes the sky through a different filter, in temporal sequence r', i', u', z', and g'. The pixel size is $24\mu m$ ($0.396''$ on the sky). The FWHM point spread function is required to be $\leq 1.1''$ in $0.8''$ free-air seeing. The imaging survey is taken in drift-scan (time-delay-and-integrate, or TDI) mode, i.e. the camera continually sweeps the sky, and a given point on the sky passes through the five filters in succession. The effective integration time per filter is 54.1

seconds, and the time for passage over the entire photometric array is about 5.7 minutes (strategy/strategy.htm; Gunn et al. 1998). Since the camera contains six columns of CCDs, the result is a long *strip* of six *scanlines*, containing almost simultaneously observed five-color data for the six CCD columns. Each CCD observes a swath of sky $13.52'$ wide. The CCDs are separated in the *row* direction (i.e. perpendicular to the scan direction) by 91.0 mm ($25.2'$ on the sky) center-to-center. The observations are filled in by a second strip, offset from the first by 93% of the CCD width, to produce a filled *stripe*, $2.54°$ wide, with 8% ($1'$) lateral overlap on each side.

Because of the camera's large field of view, the TDI tracking must be done along great circles. The Northern Galactic Cap is covered by 45 great-circle arcs. Between the lateral overlaps in a stripe and the convergence of the stripes near the poles of the survey area (Figure 1), about 40% of the sky will be imaged at least twice, at random intervals ranging from days to years.

2.3.   Photometry and Photometric Calibration

The five filters in the imaging array of the camera, $[u', g', r', i'$ and $z']$ have effective wavelengths of [3550 Å, 4770 Å, 6230 Å, 7620 Å and 9130 Å] (Fukugita et al. 1996; Gunn et al. 1998). The limiting (5:1 signal to noise ratio) point source magnitudes are [22.3, 23.3, 23.1, 22.3 and 20.8] at the survey's median air mass of 1.4 in a single scanned observation. At this writing, the observed sensitivity limits are very close to this design goal. The expected systematic magnitude uncertainties due to uncertainties in the zero point and atmospheric extinction (for point sources bright enough that systematic uncertainties dominate, i.e. brighter than $\sim 20^m$) are required to be 0.02 in r', 0.02 in $r' - i'$ and $g' - r'$, and 0.03 in $u' - g'$ and $i' - z'$. The imaging data saturate at about [13, 14, 14, 14, 12] for point sources.

The magnitude scale is on the AB_ν system (Oke 1969, unpublished), which was updated to the AB_{79} system by Oke & Gunn (1983) and to AB_{95} by Fukugita et al. (1996). The magnitudes are related to flux density f by $2.5 \log_{10}(e) \sinh^{-1}(f/b)$ (b is a constant in each band) rather than logarithmically. This definition is essentially identical to the logarithmic magnitude at signal-to-noise ratios greater than about 5 and is well behaved for low and even zero and negative flux densities (Lupton, Gunn & Szalay 1999).

The calibration and definition of the magnitude system is carried out by the USNO 1 m telescope and the 0.5m PT. The SDSS photometry is placed on the AB_ν system using three *fundamental standards* (BD + 17°4708, BD + 26°2606, and BD + 21°609), whose magnitude

scale is as defined by Fukugita et al. (1996); a set of some 100-150 *primary standards*, which are calibrated by the above fundamental standards using the USNO 1m telescope, and which cover the whole range of right ascension and enable the calibration system to be made self-consistent; and a set of *secondary calibration patches* lying across the imaging stripes, containing stars fainter than 14^m whose magnitudes are calibrated by the PT with respect to those of the primary standards and which transfer that calibration to the imaging survey. On nights when the 2.5 m is observing, the PT observes primary standard stars to provide the atmospheric extinction coefficients over the night and confirm that the night is photometric. The standard star network is described by Smith et al. (2000) and in `photcal/photcal.htm` — note that the telescope described in the latter discussion has now been replaced by the 0.5m PT (Uomoto et al. 2000a).

2.4. Astrometric Calibration

The camera also contains leading and trailing *astrometric arrays* — narrow, neutral-density-filtered, r'-filtered CCDs covering the entire width of the camera. These arrays can measure the properties of objects in the magnitude range $r' \sim 8.5$ - 16.8, i.e. cover the dynamic range between the standard astrometric catalog stars and the brightest unsaturated stars in the photometric array. The astrometric calibration is thereby referenced to the fundamental astrometric catalogues (see `astrom/astrom.htm`, Pier et al. 2000b). The astrometric accuracy (rms) is currently better than about 150 milliarcseconds (mas) in each coordinate, and the goal is an accuracy of 100 mas.

2.5. Imaging Survey: North Galactic Cap

The imaging survey covers about 10,000 contiguous square degrees in the Northern Galactic Cap. This area lies basically above Galactic latitude 30°, but its footprint is adjusted slightly to lie within the minimum of the Galactic extinction contours (Schlegel, Finkbeiner & Davis 1998), resulting in an elliptical region. The region is centered at $\alpha = 12^h\ 20^m$, $\delta = +32.5°$. The minor axis is at an angle 20° East of North with extent ±55°. The major axis is a great circle perpendicular to the minor axis with extent ±65°. The survey footprint with the location of the stripes is shown in Figure 1 — see `strategy/strategy.htm` and Kron et al. (2000) for details.

2.6. Imaging Survey: The Southern Galactic Cap

In the Southern Galactic Cap, three stripes will be observed, one along the Celestial Equator and the other two north and south of the equator. The *equatorial stripe* ($\alpha = 20.7^h$ to 4^h, $\delta = 0°$) will be observed repeatedly, both to find variable objects and, when co-added, to reach magnitude limits about 2^m deeper than the Northern imaging survey.

The other two stripes will cover great circles lying between α, δ of (20.7^h, -5.8° $\rightarrow 4.0^h$, -5.8°) and ($22.4^h, 8.7° \rightarrow 2.3^h$, 13.2°).

2.7. The Spectroscopic Survey

Objects are detected in the imaging survey, classified as point source or extended, and measured, by the image analysis software (see below). These imaging data are used to select objects in different classes whose spectra will be taken. The final details of this *target selection* will be described once the survey is underway by Newberg et al. (2000), Strauss et al. (2000) and Eisenstein et al. (2000); the criteria discussed here are likely to be very close to those finally used.

Two samples of *galaxies* are selected from the objects classified as "extended". About 9×10^5 galaxies will be selected to have Petrosian (1976) magnitudes $r'_P \leq 17.65$. Galaxies with a Petrosian surface brightness in r' fainter than 23 magnitudes/arc second^2 will be rejected from the sample, since spectroscopic observations are unlikely to produce a redshift. For illustrative purposes, a simulation of a slice of the SDSS redshift survey is shown in Figure 2 (from Colley et al. 2000). Galaxies in this CDM simulation are 'selected' by the SDSS selection criteria. As Figure 2 demonstrates, the SDSS volume is large enough to contain a statistically significant sample of the largest structures predicted. The details of galaxy target selection will be described by Strauss et al. (2000).

The second sample, of approximately 10^5 galaxies, exploits the characteristic very red color and high metallicity (producing strong absorption lines) of the most luminous galaxies: the "Brightest Cluster Galaxies" or "Bright Red Galaxies" (BRGs); redshifts can be well measured with the SDSS spectra for these galaxies to about $r' = 19.5$. Galaxies located at the dynamical centers of nearby dense clusters often have these properties. Reasonably accurate photometric redshifts (Connolly et al. 1995; Eisenstein et al. 2000) can be determined for these galaxies, allowing the selection by magnitude and $g'r'i'$ color of an essentially *distance limited* sample of the highest-density regions of the Universe to a redshift of about 0.45 (see Figure 3 for a simulation).

With their power-law continua and the influence of Lyman-α emission and the Lyman-α forest, *quasars* have $u'g'r'i'z'$ colors quite distinct from those of the vastly more numerous stars over most of their redshift range (Fan 1999). Thus about 1.5×10^5 *quasar candidates* are selected for spectroscopic observations as outliers from the stellar locus (cf., Krisciunas et al. 1998; Lenz et al. 1998; Newberg et al. 1999; Figure 5 below) in color-color space. At the cost of some loss of efficiency, selection is allowed closer to the stellar locus around z = 2.8, where quasar colors approach those of early F and late A stars (Newberg & Yanny 1997; Fan 1999). Some further regions of color-color space outside the main part of the stellar locus where quasars are very rarely found are also excluded: the regions containing M dwarf-white dwarf pairs, early A stars and white dwarfs (see Figure 5) are excluded. The SDSS will compile a sample of quasars brighter than $i' \approx 19$ at $z < 3.5$; at redshifts between 3.5 and about 5.2 the limiting magnitude will be about $i = 20$–21. Objects are also required to be point sources, except in the region of color-color space where low-redshift quasars are expected to be found (see Figure 5). Stellar objects brighter than $i' = 20$ which are FIRST sources (Becker, White and Helfand 1995) are also selected. Based on early spectroscopy, we estimate that roughly 65% of our quasar candidates are genuine quasars; comparison with samples of known quasars indicates that our completeness is of order 90%. Quasar target selection will be described in detail by Newberg et al. (2000).

In all cases, the magnitudes of the objects are corrected for Galactic extinction before selection, using extinction in the SDSS bands calculated from the reddening map of Schlegel, Finkbeiner & Davis (1998) to a uniform magnitude limit *outside* the Galaxy. If this correction were not made, the systematic effects of Galactic extinction over the survey area would overwhelm the statistical uncertainties in the SDSS data set. After the imaging and spectroscopic survey is completed in a given part of the sky, the reddening and extinction will be recalculated using internal standards extracted from the imaging data.

Together with various classes of calibration stars and fibers which observe blank sky to measure the sky spectrum, the selected galaxies and quasars are mapped onto the sky, and 'tiled', i.e. their location on a 3° diameter plug plate determined (`tiling/tiling.htm`; Lupton et al. 2000a). Excess fibers are allocated to several classes of rare or peculiar objects and to samples of stars. The spectra are observed, 640 at a time (with a total integration time of 45 minutes) using a pair of fiber-fed double spectrographs (`spectro/spectro.htm`; Uomoto et al. 2000b). The wavelength coverage of the spectrographs is continuous from about 3800 Å to 9200 Å, and the wavelength resolution, $\lambda/\delta\lambda$, is about 2000. The fibers are located at the focal plane via plug plates constructed for each area of sky. The fiber diameter is 0.2 mm ($3''$ on the sky), and adjacent fibers cannot be located more closely than $55''$ on the sky. Both members of a pair of objects closer together than this can be observed spectroscopically if they are located in the overlapping regions of adjacent tiles.

3. Software and Data Products

The operational software is described in `datasys/datasys.htm`. The data are obtained using the Data Acquisition (DA) system at APO (Petravick et al. 1994, Annis et al. 2000) and recorded on DLT tape. The imaging data consist of full images from all CCDs of the imaging array, cut-outs of detected objects from the astrometric array, and bookkeeping information. These tapes are shipped to Fermilab by express courier and the data are automatically reduced through an interoperating set of software pipelines operating in a common computing environment (Kent et al. 2000).

The *photometric pipeline* (Lupton et al. 2000b) reduces the imaging data; it corrects the data for data defects (interpolation over bad columns and bleed trails, finding and interpolating over 'cosmic rays', etc), calculates overscan (bias), sky and flat field values, calculates the point spread functions (psf) for the whole run, finds objects, combines the data from the five bands, carries out simple model fits to the images of each object, deblends overlapping objects, and measures positions, magnitudes (including psf and Petrosian magnitudes) and shape parameters. The photometric pipeline uses position calibration information from the astrometric array reduced through the *astrometric pipeline* (Pier et al. 2000b) and photometric calibration data from the photometric telescope, reduced through the *photometric telescope pipeline* (Tucker et al. 2000). Final calibrations are applied by the *final calibration pipeline*, which allows refinements in the positional and photometric calibration to be applied to the data as the survey progresses. The photometric pipelines are extensively tested using repeat observations, examination of the outputs, observations of regions of the sky by other telescopes (HST fields, for example) and a set of simulations, described in detail in `simul/simul.htm`.

The outputs, together with all the observing and processing information, are loaded into the *operational data base* (Yanny et al. 2000b), which is the central collection of scientific and bookkeeping data used to run the survey. To select the spectroscopic targets, objects are run through the *target selection pipeline* (Vanden Berk et al. 2000) and flagged if they meet the selection criteria for a particular type of object. The criteria for the primary objects (quasars, galaxies and BRGs) will not be changed once the survey is underway. Those for serendipitous objects and samples of interesting stars can be changed throughout the survey. A given object can in principle receive several target flags. The selected objects are tiled as described above, plug plates are drilled, and the spectroscopic observations are made. The spectroscopic data are automatically reduced by the *spectroscopic pipeline* (Frieman et al. 2000), which extracts, corrects and calibrates the spectra, determines the spectral type, and measures the redshift. The reduced spectra are then stored in the operational data base. The contents of the operational data base are copied at regular intervals into the *science data*

base (Szalay et al. 2000) for retrieval and scientific analysis (see `appsoft/appsoft.htm`). The science data base is indexed in a hierarchical manner, the data and other information linked into 'containers' that can be divided and subdivided as necessary, to define easily searchable regions with approximately the same data content. This hierarchical scheme is consistent with those being adopted by other large surveys, to allow cross referencing of multiple surveys. The science data base also incorporates a set of query tools and is designed for easy portability.

The photometric data products of the SDSS include: a *catalog* of all detected objects, with measured positions, magnitudes, shape parameters, model fits and processing flags; *atlas images* (i.e. cutouts from the imaging data in all five bands) of all detected objects and of objects detected in catalogs made at other wavelengths; a 4×4 binned image of the corrected images with the objects removed: and a *mask* of the areas of sky not processed (because of saturated stars, for example) and of corrected pixels (those for which cosmic rays were removed, for example). The photometric outputs will be described in detail by Lupton et al. (2000b); for now see `http://www.astro.princeton.edu/SDSS/photo.html`. The data base will also contain the calibrated 1D *spectra*, the derived *redshift* and *spectral type*, and the bookkeeping information related to the spectroscopic observations. In addition, the positions of astrometric calibration stars measured by the astrometric pipeline and the magnitudes of the faint photometric standards measured by the photometric telescope pipeline will be published at regular intervals.

4.   Early Science from the SDSS Commissioning Data

The goal of the SDSS is to provide the data necessary for studies of the large scale structure of the Universe on a wide range of scales. The imaging survey should detect $\sim 5 \times 10^7$ galaxies, $\sim 10^6$ quasars and $\sim 8 \times 10^7$ stars to the survey limits. These photometric data, via photometric redshifts and various statistical techniques such as the angular correlation function, support studies of large scale structure well past the limit of the spectroscopic survey. On even larger scales, information on structure will come from quasars and from the absorption features in their spectra.

The science justification for the SDSS is discussed in several conference papers (e.g. Gunn & Weinberg 1995; Fukugita 1998; Margon 1999). The Project Book science sections can be accessed at `http://www.astro.princeton.edu/PBOOK/science/science.htm`. Much of the science for which the SDSS was built, the study of large scale structure, will come when the survey is complete, but the initial test data have already led to significant scientific discoveries in many fields. In this section, we show examples of the first test data

and some initial results. To date, the SDSS has obtained test imaging data for some 450 square degrees of sky and about 10,000 spectra. Examples of these data are shown in Figures 4 (a composite color image of a piece of the sky which contains the cluster Abell 267), 5 (sample color-color and color-magnitude diagrams of point-source objects), and 6 (sample spectra).

Fischer et al. (2000) have detected the signature of the weak lensing of background galaxies by foreground galaxies, allowing the halos and total masses of the foreground galaxies to be measured. Jain et al. (2000) have calculated the angular correlation function between low- and high-redshift galaxies (selected using photometric redshifts) and have found indications of the negative correlation due to lensing of the background sample.

The searches by Fan et al. (1999a,b; 2000a) and Schneider et al. (2000) have greatly increased the number of known high redshift (z>3.6) quasars and include the only two known quasars with redshifts ≥ 5.0. Fan et al. (1999b) have found the first example of a new kind of quasar: a high redshift object with a featureless spectrum and without the radio emission and polarization characteristics of BL Lac objects. The redshift for this object ($z = 4.6$) is found from the Lyman-α forest absorption in the spectrum.

Some 150 distant probable RR Lyrae stars have been found in the Galactic halo, enabling the halo stellar density to be mapped; the distribution may have located the edge of the halo at approximately 60 kpc (Ivezić et al. 2000). The distribution of RR Lyrae stars and other horizontal branch stars is very clumped, showing the presence of possible tidal streamers in the halo (see also Yanny et al. 2000a). Margon et al. (1999) describe the discovery of faint high latitude carbon stars in the SDSS data; these objects will also enable the halo to be mapped.

Strauss et al. (1999), Schneider et al. (2000), Fan et al. (2000b), Tsvetanov et al. (2000) and Pier et al. (2000a) report the discovery of a number of very low mass stars or substellar objects, those of type 'L' or 'T', including the first field methane ('T') dwarfs. The detection rate to date shows that the SDSS is likely to identify several thousand L and T dwarfs. These objects are found to occupy very distinct regions of color-color and color-magnitude space, which will enable the completeness of the samples to be well characterized.

Measurements of the psf diameter variations and the image wander allow variations in the turbulence in the Earth's atmosphere to be tracked. These data demonstrate the presence of anomalous refraction on scales at least as large as the 2.3° field of view of the camera (Pier et al. 2000b).

Of course the most exciting possibility for any large survey which probes new regions of sensitivity or wavelength is the discovery of exceedingly rare or entirely new classes of

objects. The SDSS has already found a number of very unusual objects; the nature of some of these remains unknown (Fan et al. 2000c). These and other investigations in progress show the promise of SDSS for greatly advancing astronomical work in fields ranging from the behavior of the Earth's atmosphere to structure on the scale of the horizon of the Universe.

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Fig. 1.— Projection on the sky (Galactic coordinates) of the Northern and Southern SDSS surveys. The lines show the individual stripes to be scanned by the imaging camera. These are overlaid on the extinction contours of Schlegel, Finkbeiner and Davis (1998). The Survey pole is marked by the 'X'.

Fig. 2.— A six-degree wide slice of the Simulated Sloan Digital Sky Survey (from Colley et al. 1999), showing about 1/20 of the survey.

Fig. 3.— Simulated redshift distribution in a $6°$ slice of the SDSS. Small (black) dots: main galaxy sample (cf. Figure 2). Large (red) dots: the BRG sample, showing about 1/30 of the survey.

Fig. 4.— A sample frame ($13' \times 9'$) from the SDSS imaging commissioning data. The image, a color composite made from the g', r', and i' data, shows a field containing the distant cluster Abell 267 ($\alpha = 01^h 52^m 41.0^s$, $\delta = +01° 00' 24.7''$, redshift $z = 0.23$, Crawford et al. 1999); this is the cluster with yellowish colors in the lower center of the frame. The frame also contains, in the upper center, the nearby cluster RX J0153.2+0102, estimated redshift ~ 0.07 (Bade et al. 1998) ($\alpha = 01^h 53^m 15.15^s$, $\delta = +01° 02' 18.8''$). The psf (optics plus seeing) was about $1.6''$. Right ascension increases from bottom to top of the frame, declination from left to right.

Fig. 5.— Color-color and color-magnitude plots of about 117,000 point sources brighter than 21^m at i^* and detected at greater than 5σ in each band from 25 square degrees of SDSS imaging data, reduced by the photometric pipeline (the i^* designation is used for preliminary SDSS photometry). The contours are drawn at intervals of 10% of the peak density of points.

Fig. 6.— Representative SDSS spectra taken from a single spectroscopic plate observed on 4 October 1999 for a total of one hour of integration time, processed by the SDSS spectroscopic pipeline. For display purposes, all spectra have been smoothed with a 3-pixel boxcar function. All spectra show significant residuals due to the strong sky line at 5577Å. The objects depicted are: a. An $r_P^* = 18.00$ galaxy; $z = 0.1913$. This object is slightly fainter than the main galaxy target selection limit. Note the Hα/[N II] emission at ~ 7800Å, [OII] emission at ~ 4450Å, and H and K absorption at ~ 4700Å. b. An $r_P^* = 19.41$ galaxy, $z = 0.3735$. This object is close to the photometric limit of the Bright Red Galaxy sample. The H and K lines are particularly strong. c. A star-forming galaxy with $r_P^* = 16.88$, at $z = 0.1582$. d. A $z = 0.3162$ quasar, with $r_{psf}^* = 16.67$. Note the unusual profile shape of the Balmer lines. This quasar is LBQS 0004+0036 (Morris et al. 1991). e. A $z = 2.575$ quasar with $r_{psf}^* = 19.04$; note the resolution of the Lyman-α forest. This quasar was discovered by Berger & Fringant (1985). f. A hot white dwarf, with $r_{psf}^* = 18.09$.