The Sloan Digital Sky Survey

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\textbf{Abstract.} The Sloan Digital Sky Survey (SDSS) will carry out a digital photometric and spectroscopic survey over $\pi$ steradians in the northern Galactic cap. An array of CCD detectors used in drift-scan mode will image the sky in five passbands to a limiting magnitude of $r' \sim 23$. Selected from the imaging survey, $10^6$ galaxies, $10^5$ quasars and selected samples of stars will be observed spectroscopically. In addition, a smaller ($225 \text{ deg}^2$), deeper, southern survey will reach $\sim 2.0$ magnitudes fainter and will contain a wealth of information about variable sources, supernovae and proper motions. We describe the current status of the survey, which recently saw first light, and its prospects for constraining cosmological models.

1 Survey Overview

The SDSS consists of two surveys, one photometric and one spectroscopic. To complete a digital survey over a large fraction of the sky within a finite amount of time, it is necessary to conduct wide-field imaging and multi-object spectroscopy. To meet this need, a wide-field telescope, imaging camera and multi-fibre spectrographs were designed and built specifically for this purpose.

The alt-az telescope uses a modified Ritchey-Chr\'etien design \cite{2}, with a primary aperture of 2.5m and a focal ratio of f/5 to produce a flat field of 3\textdegree with a plate scale of 16.51 arcsec/mm. It is situated at Apache Point Observatory, near Sunspot, New Mexico, at a height of 2,800m. The telescope is housed in an enclosure which rolls off for observing, and is encased in a co-rotating baffle which protects it from wind disturbances and stray light. This unique design allows the telescope to remain free of dome-induced seeing. First-light images and recent photographs of the site and telescope can be found at \url{http://www.sdss.org/}. Technical details about the survey can be obtained from \url{http://www.astro.princeton.edu/BBOOK/}.

1.1 Imaging Survey

The photometric imaging survey will produce a database of roughly $10^8$ galaxies and $10^8$ stellar objects, with accurate ($\leq 0.10$ arcsec) astrometry, 5-colour ($u', g', r', i'$ and $z'$) photometry, and object classification parameters. This database will become a public archive.
The imaging camera consists of 54 CCDs in eight dewars and spans 2.3° on the sky. Thirty of these CCDs are the main imaging/photometric devices, each a SITE (Scientific Imaging Technologies, formerly Tektronix) device with 2048x2048 24µ pixels. They are arranged in six column dewars of 5 CCDs each, one CCD for each filter bandpass in each column. The camera will be operated in TDI (Time Delay and Integrate), or scanning, mode for which the telescope will be driven at a rate synchronous with the charge transfer rate of the CCDs. Objects on the sky will drift down columns of the CCDs so that nearly simultaneous 5-colour photometry will be obtained with no dead-time. The effective integration time, i.e. the time any part of the sky spends on each chip, is 55 seconds at the chosen (sidereal) scanning rate, which will result in a limiting magnitude of \( r' \sim 23 \).

The SDSS photometric system has been specifically designed for this survey and covers the near-UV to near-IR range (\( \sim 3000–10000 \)Å). In order to provide photometric calibration while the imaging camera is scanning, a second, dedicated Monitor Telescope will be in operation, observing photometric standard stars and creating photometrically calibrated “secondary patches” which lie within the main telescope’s scan. These calibration patches will then be used to transfer the primary photometric calibration to objects detected with the 2.5m telescope and imaging camera.

The other 24 CCDs in two additional dewars are also SITE chips of width 2048 24µ pixels, but they have only 400 rows in the scanning direction. These dewars are oriented perpendicular to the photometric dewars and one lies across the top of the columns, the other across the bottom. Two of these CCDs (one in each dewar) will be used to determine changes in focus. The other 22 CCDs will reach brighter magnitudes before saturating and are used to tie observations to an astrometric reference frame.

The northern survey area is centered near the North Galactic Pole and it lies within a nearly elliptical shape 130° E-W by 110° N-S chosen to minimize galactic foreground extinction. All scans will be conducted along great circles in order to minimize the transit time differences across the camera array. There are 45 great circles (“stripes”) in the northern survey region separated by 2.5°. Each stripe will be scanned twice, with an offset perpendicular to the scan direction in order to interlace the photometric columns. A completed stripe width will slightly exceed 2.5° and thus there will be a small amount of overlap to allow for telescope mis-tracking and to provide multiple observations of some fraction of the sky for quality assurance analysis. The total stripe length will require a minimum of 650 hours of pristine photometric and seeing conditions to scan at a sidereal rate. Based upon historical records of observing conditions at APO, we are allowing 5 years to complete the survey.

1.2 Spectroscopic Survey

The spectroscopic survey will observe spectra for \( 10^6 \) galaxies, \( 10^5 \) QSOs and \( 10^5 \) stars. In order to obtain the spectra of over \( 10^6 \) objects in a survey
covering $10^4$ square degrees, we must get spectra of about 100 objects per square degree. Although some overlap of fields is inevitable, we would like to keep this overlap to a minimum for reasons of efficiency and cost. Hence we need to obtain several hundred spectra per 3°diameter spectroscopic field.

To accommodate this requirement, two identical multi-fibre spectrographs have been built which will each be fed by 320 fibres. The spectrographs cover 3900–9100Å with a resolution of $\lambda/\Delta\lambda \sim 1800$, or 167 km s$^{-1}$. Each spectrograph has two cameras, one optimized for the red and the other for the blue. Each camera has as its detector a 2048x2048 CCD with 24 $\mu$ pixels.

The 180 $\mu$ (3′′ on the sky) fibres are located in the focal plane by plugging them by hand into aluminum plates which are precisely drilled for each field based upon the astrometric solution obtained from the imaging data. To avoid mechanical interference, individual fibres can be placed no closer than 55′′ to one another. The plates and fibres are held in the focal plane, and coupled with the spectrographs, by one of 9 identical rigid assemblies called cartridges. Since all of the cartridges can be pre-plugged during the day, 5,760 spectra can be obtained during a long night without re-plugging. A mapping procedure will be invoked after plugging each cartridge that will tag each fibre to the appropriate object on the sky.

To obtain redshifts for galaxies to a limiting magnitude of $r' \sim 18$ will require exposure times of about 45 minutes, consisting of three 15 minute exposures. Each field should take about an hour, including calibration (flat field and comparison lamp) exposures and allowing for telescope pointing and the exchange of fibre cartridges.

1.3 Data Processing

All of the raw data from the photometric CCDs are archived. The frames are first read to disk, then written to DLT tape. Over 16 Gb per hour are generated from the photometric chips. When observing in spectroscopic mode, the amount of data generated seems trivial in comparison (about 6 exposures per hour for each of two cameras for each of two spectrographs, or 24 8Mb frames per hour).

All data tapes are shipped by overnight express courier to Fermi National Accelerator Laboratory (near Chicago) where the software data reduction pipelines will be run. The goal is to be able to turn the imaging data around within a few days, so that one dark run’s worth of data will be processed before the next dark run begins, allowing objects to be targeted for spectroscopy. The data flow serially through several pipelines to identify, measure and extract astronomical images and to apply photometric and astrometric calibrations. Once a significant area of sky has been imaged, a target selection procedure will be run in order to select objects for followup spectroscopy. Spectroscopic reduction will be automated, with the aim of obtaining redshifts for 99% of targeted objects without human intervention. The pipelines are integrated into a specially-written environment known as Dervish, and the reduced data
will be written into an object-oriented database.

1.4 Spectroscopic Samples

There will be several distinct spectroscopic samples observed by the survey. In a survey of this magnitude, it is important that the selection criteria for each class remain fixed throughout the duration of the survey. Therefore, we plan to spend a whole year obtaining test data with the survey instruments and refining the spectroscopic selection criteria in light of our test data. Then, once the survey proper has commenced, these criteria will be “frozen in” for the duration of the survey. The numbers discussed below are therefore only preliminary, and we expect them to change slightly during the test year.

The main galaxy sample will consist of $\sim 900,000$ galaxies selected by Petrosian magnitude in the $r'$ band, $r' \leq 18$. Simulations have shown that the Petrosian magnitude, which is based on an aperture defined by the ratio of light within an annulus to total light inside that radius, provides probably the least biased and most stable estimate of total magnitude. There will also be a surface-brightness limit, so that we do not waste fibres on galaxies of too low surface brightness to give a reasonable spectrum. This galaxy sample will have a median redshift $\langle z \rangle \approx 0.1$.

We plan to observe an additional $\sim 100,000$ luminous red galaxies to $r' \leq 19.5$. Given photometry in the five survey bands, redshifts can be estimated for the reddest galaxies to $\Delta z \approx 0.02$ or better \cite{3}, and so one can also predict their luminosity quite accurately. Selecting luminous red galaxies, many of which will be cD galaxies in cluster cores, provides a valuable supplement to the main galaxy sample since 1) they will have distinctive spectral features, allowing a redshift to be measured up to 1.5 mag fainter than the main sample, and 2) they will form an approximately volume-limited sample with a median redshift $\langle z \rangle \approx 0.5$. They will thus provide an extremely powerful sample for studying clustering on the largest scales and galaxy evolution.

Quasar candidates will be selected by making cuts in multi-colour space and from the FIRST radio catalogue \cite{1}, with the aim of observing $\sim 100,000$ quasars. This sample will be orders of magnitude larger than any existing quasar catalogue, and will be invaluable for quasar luminosity function, evolution and clustering studies as well as providing sources for followup absorption-line observations.

In addition to the above three classes of spectroscopic sources, which are designed to provide statistically complete samples, we will also obtain spectra for many thousands of stars and for various serendipitous objects. The latter class will include objects of unusual colour or morphology which do not fit into the earlier classes, plus unusual objects found by other surveys and in other wavebands.


2 Current Status

The 2.5m telescope and imaging camera are complete and in place. First light with the imaging camera was obtained on 9 May 1998 during bright time and without the baffles; subsequently two imaging runs were made during dark time and with the baffles in place. The image size was 0.95–1.1″ for the second dark run.

The spectrographs are both at the site and all optics have been completed and coated. One spectrograph has been fully assembled and some test spectra taken. A fully assembled fibre cartridge is ready and all the others are ready for assembly. The full complement of over 6,000 science fibres needed for the survey have been accepted and tested with a mean throughput of 92.0\%. Test plug plates have been drilled with all positions well within tolerances. The various pieces of equipment for storing, handling, and transporting the cartridges are all in place. Once the telescope control system is in operation later this year, we will be able to take spectra on the sky.

All of the data reduction-pipelines are written, with ongoing work on minor bug-fixes, speed-ups and integration of the entire data processing system. The imaging/photometric reduction pipelines are being exercised with the data taken this May and June by the survey imaging camera. Tests are being carried out on the spectroscopic reduction pipeline using simulated data.

The intent of this project is to make the survey data available to the astronomical community in a timely fashion. We currently plan to distribute the data from the first two years of the survey no later than two years after it is taken, and the full survey no later than two years after it is finished. The first partial release may or may not be in its final form, depending on our ability to calibrate it fully at the time of the release. The same remarks apply to the release of the full data set, but we expect the calibration effort to be finished before that release.

3 Some Cosmological Highlights

The main impetus for carrying out the Sloan survey is to provide definitive measures of the local (z < 0.5) large-scale structure in the Universe. The huge volume of the SDSS redshift survey will enable reliable estimates of the galaxy power spectrum to ~ Gpc scales, thus allowing one to constrain the shape of the primordial spectrum predicted by linear perturbation theory (Figure 1). Comparison with CMB anisotropy data, particularly the upcoming MAP and Planck surveys, will allow a direct measurement of galaxy bias $b$ over a wide range of scales. Measurements of higher-order galaxy clustering (Frieman, these proceedings) and redshift space distortions will provide further constraints on the density parameter $\Omega_0$ and $b$.

Clues to the physics of galaxy formation will be provided by studying the luminosity function and clustering of galaxies separated by colour, morphology
and other intrinsic galaxy properties. Photometric redshifts will make the Sloan dataset an extremely powerful one for studying galaxy evolution over a range of redshifts beyond that reached by the spectroscopic survey.

We also plan to search for low surface brightness (LSB) galaxies in the Sloan imaging data. The drift-scan observing mode means that detection of LSB objects is limited by photon statistics rather than flat-fielding errors, and we expect to detect galaxies with a central surface brightness as low as $\mu_0 \approx 27.5$ mag arcsec$^{-2}$ in the $r'$ band. One of the survey products will be a $4 \times 4$ binned sky map, from which we will be able to find galaxies to a surface brightness of yet four times less.

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