The Sloan Digital Sky Survey

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Abstract

The Sloan Digital Sky Survey (SDSS) is making a multi-colour, three dimensional map of the nearby Universe. The survey is in two parts. The first part is imaging one quarter of the sky in five colours from the near ultraviolet to the near infrared. In this imaging survey we expect to detect around 50 million galaxies to a magnitude limit \( g \sim 23 \). The second part of the survey, taking place concurrently with the imaging, is obtaining spectra for up to 1 million galaxies and 100,000 quasars. From these spectra we obtain redshifts and hence distances, in order to map out the three-dimensional distribution of galaxies and quasars in the Universe. These observations will be used to constrain models of cosmology and of galaxy formation and evolution.

This article describes the goals and methods used by the SDSS, the current status of the survey, and highlights some exciting discoveries made from data obtained in the first two years of survey operations.

1 Introduction

What is the Universe made of? How did the Universe begin? How will it end?

These are some of the fundamental questions which can be addressed by studying the large scale distribution of galaxies in the Universe. It is widely believed that the galaxies we see today formed at the sites of tiny (~ 1 part in \( 10^5 \)) density fluctuations in the early Universe. The form of these density fluctuations (which, if Gaussian in nature, may be fully described by their power spectrum) are predicted by cosmological models, and depend on such parameters as the mean matter density \( \Omega_m \), the fraction of baryonic matter \( \Omega_b/\Omega_m \) and any contribution to the cosmological density from vacuum energy, also known as the cosmological constant \( \Omega_\Lambda \). On large scales, the clustering of galaxies can be predicted from the primordial density fluctuations using linear perturbation theory. By measuring this large-scale clustering, we can thus obtain important constraints on cosmological models. By studying the intrinsic properties of the galaxies themselves, such as luminosity, colour and morphology, we can test theories for how galaxies are born and evolve.

In order to measure the clustering of galaxies reliably, it is important to use a systematic and well-defined catalogue. Systematic surveys date back to that of Messier, published in three parts in the 1770s and 1780s, although it was not realized at the time that some of the nebulae catalogued by Messier were other galaxies outside our own Milky Way. It was only in 1923, by a careful measurement of the distance to the Andromeda Nebula (M31 in Messier’s catalogue), that Edwin
Hubble proved definitively that M31 was a large galaxy separate from our own. Hubble later discovered the expansion of the Universe, and found that the recession velocity of a galaxy is in direct proportion to its distance from us, the Hubble law. Since then, a number of galaxy surveys have been published, starting with that of Shapley and Ames in 1932 [33], and including more recently the APM Galaxy Survey [24], which contains positions and magnitudes for about three million galaxies. Most of these surveys are based on photographic plates, and there is concern that such surveys could be missing a substantial fraction of low surface-brightness galaxies, eg. [8]. There is also apprehension that uncertainties in the photometric calibration of these surveys could lead to spurious measurement of galaxy clustering on large scales [12, 23].

Smaller surveys have been made using charge coupled device (CCD) detectors. These solid state devices, unlike photographic plates, have a linear response to light and \( \sim 50 \) times higher quantum efficiency, but the limited size of these detectors has before now precluded the construction of wide-area galaxy surveys.

In order to map out the three-dimensional distribution of galaxies, as opposed to just their two-dimensional projection on the celestial sphere, one needs the distance to each galaxy. This may be obtained by measuring the spectrum of light emitted by a galaxy. The Doppler shift in features towards the red end of the spectrum (the redshift) may be used to infer a galaxy’s recession velocity and hence its distance from the Hubble relation. Until recently, galaxy spectra were painstakingly measured one-by-one, and it is only in the last few years that optical fibre multiplexing has been used to measure redshifts for many thousands of galaxies.

The largest redshift survey to date is the nearly-completed Two Degree Field (2dF) Galaxy Redshift Survey carried out on the Anglo-Australian Telescope [6]. While containing redshifts for more than 200,000 galaxies, the 2dF survey is based on the photographic APM Galaxy Survey, with the potential problems mentioned above.

The Sloan Digital Sky Survey (SDSS) collaboration was therefore formed in 1988 with the aim of constructing a definitive map of the local universe, incorporating CCD imaging in several passbands over a large area of sky, and measurement of redshifts for around one million galaxies. In order to complete such an ambitious project over a reasonable timescale, it was decided to build a dedicated 2.5-metre telescope equipped with a large CCD array imaging camera and multi-fibre spectrographs. The survey itself began in April 2000, and observations are scheduled to finish in June 2005. In this article I review some important aspects of the survey, including an overview of survey operations (§2), a description of the preliminary public data release (§3), and a selection of some early science results (§4).

## 2 Survey Overview

### 2.1 Goals

The basic goal of the survey is to make a definitive map of the local Universe, which can then be used to constrain cosmological models and models for the formation and evolution of galaxies. This map will consist of 5-colour imaging to a \( g \)-band limiting magnitude \( m \approx 23 \) over a contiguous area of \( \pi \) steradians (10,000 square degrees) in the northern sky and three, non-contiguous stripes with total area 740 square degrees in the southern sky. (Magnitudes measure flux on a logarithmic scale,
where smaller magnitudes correspond to larger flux. The magnitude difference between two stars of flux $f_1$ and $f_2$ is defined to be $m_1 - m_2 = -2.5 \log(f_1/f_2)$. The brightest stars have magnitude $m \approx 1$, the faintest stars visible to the naked eye have $m \approx 6$, i.e. 100 times fainter. A magnitude $m \approx 23$ thus corresponds to an observed flux which is roughly six million times fainter than that of the dimmest naked-eye stars.) From this imaging data we can map out the two-dimensional distribution of galaxies and quasars as projected on the celestial sphere. Distances to a subset of these objects will be determined by observing spectra of roughly one million galaxies and 100,000 quasars. The spectrum of a galaxy or quasar enables one to measure its recession velocity $v$ from the Doppler redshift of spectral features. Distances $d$ may then be estimated from the Hubble law: $v = H_0d$, where $H_0 \approx 70$ km/s/Mpc is the Hubble parameter. In this way, we can map out the three-dimensional distribution of objects in space. (Astronomers often measure extragalactic distances in units of Mpc where 1 Mpc = $10^6$ parsecs, and 1 parsec $\approx 3.09 \times 10^{16}$m. Uncertainty in the value of $H_0$ leads to a corresponding uncertainty in distances derived from the Hubble relation. To reflect this, distances are often written in units of $h^{-1}$Mpc, where $H_0 = 100h$ km/s/Mpc.)

### 2.2 Hardware and operations

The SDSS consists of two concurrent surveys, one photometric and one spectroscopic. To complete a digital survey over a large fraction of the sky within a reasonable timescale, 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, which I describe very briefly below.

The survey hardware comprises the 2.5-metre survey telescope, a 0.5-metre photometric telescope (called the monitor telescope in its previous incarnation), a state-of-the-art imaging camera [14] that observes near-simultaneously in five passbands covering the near-ultraviolet to near-infrared, and a pair of dual beam spectrographs, each capable of observing 320 fibre-fed spectra. The site is also equipped with a 10-micron all-sky camera [17], which provides rapid warning of any cloud cover. The data are reduced by a series of automated pipelines and the resulting data products stored in an object-oriented database.

The main survey telescope is of modified Ritchey-Chrétien design [39], with a primary aperture of 2.5m and a focal ratio of f/5 to produce a flat field of 3° with a plate scale of 16.51 arc-sec/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. Photographs of the site and telescope can be found at http://www.sdss.org/. A technical overview of the survey has been given by York et al. [40] and further details are available online in the SDSS Project Book at http://astro.princeton.edu/PBOOK/welcome.htm.

### 2.3 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 photometry, and object classification parameters. This database will become a public archive.
Figure 1: Front view of the imaging camera assembly. The *ugriz* imaging CCDs are colour-coded blue, green, red, black and orange respectively. The astrometric CCDs are shown as narrow red rectangles. The arrows indicate the direction of motion of astronomical sources across the imaging array, which subtends 2.3° on the sky.
The imaging camera [14] (Figure 1) 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 $2048 \times 2048$ pixels. They are arranged in six dewars aligned with the scan direction and holding 5 CCDs each, one CCD for each filter bandpass. The camera operates in TDI (Time Delay and Integrate), or scanning, mode for which the telescope is driven at a rate synchronous with the charge transfer rate of the CCDs. Objects on the sky drift down the CCD array so that nearly simultaneous 5-colour photometry is obtained. The effective integration time, i.e. the time any part of the sky spends on each detector, is 55 seconds at the chosen (sidereal) scanning rate, which results in a limiting magnitude of $g \sim 23$.

The SDSS photometric system $u'g'r'i'z'$ [13] (Figure 2) has been specifically designed for this survey and covers the near-UV to near-IR range ($\sim 3000$–$10,000\ang$) in five essentially non-overlapping passbands. The $u$ filter response peaks in the near ultra-violet at 3500\ang, $g$ is a blue-green band centred at 4800\ang, $r$ is a red band centred at 6250\ang, $i$ is a far-red filter centred at 7700\ang and $z$ is a near-infrared passband centred at 9100\ang. The standard stars that define this system have been presented by Smith et al. [34]. The photometric data are not yet finally calibrated, so the current magnitudes are indicated with asterisks, $u^*g^*r^*i^*z^*$, to denote their preliminary nature. The SDSS filters themselves are referred to simply as $ugriz$, without primes or asterisks.

In order to provide photometric calibration while the imaging camera is scanning, a second, dedicated Photometric Telescope operates concurrently, observing photometric standard stars and creating photometrically calibrated “secondary patches” which lie within the main telescope’s scan. These calibration patches are then used to transfer the primary photometric calibration to objects detected with the 2.5m telescope and imaging camera. The photometric quality of the data is monitored by a software “robot” that automatically rejects data observed during cloudy periods [16].

The other 24 CCDs in two additional dewars are also SITe chips of width $2048 \times 24\mu$ pixels, but they have only 400 rows in the scanning direction. These dewars are oriented perpendicular to the photometric dewars, with one at the top and one at the bottom of the imaging array. Two of these CCDs (one in each dewar) are used to determine changes in focus. The remaining 22 CCDs reach brighter magnitudes before saturating and are used to tie our observations to an astrometric reference frame defined by bright stars which saturate our imaging detectors [28].

The location of the survey imaging area is shown in Figure 3. The northern survey area is centred 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 are 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°. We observe three non-contiguous stripes in the Southern Galactic Hemisphere, at declinations of 0, +15° and −10°, during parts of the autumn season when the northern sky is unobservable. Each stripe is scanned twice, with an offset perpendicular to the scan direction in order to interlace the photometric columns. A completed stripe slightly exceeds 2.5° in width and thus there is 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 purposes. The total stripe length for the 45 northern stripes will require a minimum of 650 hours of pristine photometric and seeing conditions to scan at a sidereal rate. Based upon our current experience of observing conditions at APO, it seems likely that we will only complete about 75% of this imaging after 5 years of survey operations.
Figure 2: SDSS photometric system response as a function of wavelength in Angstroms. The upper curve is without atmospheric extinction, the lower curve includes the effects of atmospheric extinction when observing at a typical altitude of 56°.
2.4 Spectroscopic Survey

The goals of the spectroscopic survey are to observe spectra for $10^6$ galaxies, $10^5$ quasars 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 obtain 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 are each fed by 320 fibres. The spectrographs cover the wavelength range 3900–9100Å at 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 2048 × 2048 CCD with 24μ pixels.

The 180μ fibres, which each subtend 3″ on the sky, are located in the focal plane by plugging them by hand into aluminium 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 is invoked after plugging each cartridge that automatically tags each fibre to the appropriate object on the sky.

A surface density of 100 galaxies per square degree corresponds roughly to an $r$-band magnitude limit $r \approx 18$. To obtain redshifts for galaxies of this magnitude requires exposure times of about 45 minutes, which we split into three, 15 minute exposures to aid in rejection of cosmic rays. Cosmic ray
events occur at essentially random locations on our detectors, and so are very unlikely to appear at the same place in all three exposures. Each field takes about one hour, including calibration (flat field and comparison lamp) exposures and allowing for telescope pointing and the exchange of fibre cartridges. Spectroscopic observations are carried out whenever observing conditions are not adequate for imaging, i.e. when seeing exceeds 1.5 arcsec or when skies are non-photometric.

2.5 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 data reduction pipelines are run. The goal is to turn the imaging data around within a few days, so that one dark run’s worth of imaging 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 is then run in order to select objects for followup spectroscopy. Next, an adaptive tiling algorithm assigns targets to spectroscopic plates and chooses plate centres in order to maximize observing efficiency [4]. Since galaxies are clustered on the sky, the target density varies from place to place. In regions of high target density, the adaptive tiling algorithm allows the plates to move slightly closer together so that all targets can be observed. The plates are then manufactured and shipped to the site.

Spectroscopic reduction is also automated. We are able to obtain correct 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 are stored in an object-oriented database.

2.6 Spectroscopic Samples

There are several distinct spectroscopic samples observed by the survey. In a survey of this magnitude, it is important that the selection criteria for each sample remain fixed throughout the duration of the survey. Therefore, we spent a whole year obtaining test data with the survey instruments and refining the spectroscopic selection criteria in light of our test data. Now that the survey proper is underway, these criteria have been “frozen in” for the duration of the survey.

The main galaxy sample [36] consists of ∼ 900,000 galaxies selected by r band magnitude, r* < 17.77. This magnitude limit was chosen as test year data demonstrated that it corresponds closely to the desired target density of 90 objects per square degree. Since galaxies are fuzzy, extended sources, there is no easy way to measure their total magnitude. Most previous surveys have measured the light within an isophote of constant surface brightness, but these isophotal magnitudes will systematically underestimate the flux of galaxies of low intrinsic surface brightness and at high redshift z, since observed surface brightness scales as (1 + z)^4. Simulations have shown
that the Petrosian magnitude [27], 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. We therefore select galaxies according to their Petrosian magnitude.
We also apply a surface-brightness limit, $\mu_r^* < 24.5 \text{ mag arcsec}^{-2}$, so that we do not waste fibres
on galaxies of too low surface brightness to give a reasonable spectrum. This surface brightness cut
eliminates just 0.1% of galaxies that would otherwise be selected for observation. Galaxies in this
sample have a median redshift $\langle z \rangle \approx 0.104$.

We will observe an additional $\sim 100,000$ luminous red galaxies [10]. Given photometry in the
five survey bands, redshifts can be estimated for the reddest galaxies to $\Delta z \approx 0.02$ or better, and
so one can also predict their intrinsic luminosities quite accurately. The luminous red galaxies,
many of which will be so-called central dominant (cD) galaxies in cluster cores, provide a valuable
supplement to the main galaxy sample since 1) they have distinctive spectral features, allowing a
redshift to be measured for objects to a flux limit around 1.5 magnitudes fainter than the main
sample, and 2) they form a volume-limited sample, i.e. a sample of uniform density, out to redshift
$z = 0.38$. This sample will thus be extremely powerful for studying clustering on the largest scales
and for investigating galaxy evolution.

Quasar candidates [29] are selected from cuts in multi-colour space and by identifying sources
from the FIRST radio catalogue [2], 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 are also obtaining spectra for many thousands of stars and for various serendipitous objects. The latter class includes 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.

2.7 Survey Status

First light with the imaging camera was obtained on 9 May 1998 and the first extra-galactic spectra
were obtained in June 1999. The survey officially began on 1 April 2000, and observing is scheduled
to end on 30 June 2005. At the time of writing (June 2002), we have imaged 4278 square degrees
(40% of the total survey area) and obtained spectra for 621 plug-plates, yielding spectra for 264,995
galaxies, 37,612 quasars and 50,023 stars, including some repeated observations. The spectrographs
are performing extremely efficiently, with an overall throughput, including telescope optics but
excluding the atmosphere, of 20% in the blue (3900–6000 Å) and 25% in the red (6000–9100 Å).
Automated spectral reduction pipelines classify these spectra and measure redshifts. Conservatively,
we inspect the spectra of roughly 8% of sources, whenever there is any doubt about the reliability
of the automated redshift measurement. In seven-eighths of these cases, the automated redshift
measurement is in fact confirmed to be correct. The remaining eighth of these spectra (1% overall)
have their redshifts manually corrected. Based on manual inspection of all $\approx 23,000$ spectra from
39 plugplates, this procedure correctly measures redshifts for 99.7% of galaxies, 98.0% of quasars
and 99.6% of stars.
3 The Early Data Release

The first public release of SDSS data (hereafter EDR) took place on 5 June 2001, and consists of images covering 460 square degrees of sky, photometric parameters for 10 million objects and spectra for 54,000 objects. The main access point to the data is through the website http://www.sdss.org/ and the EDR is described in [35].

There are presently three ways to access the data, the choice of which depends on the nature of the data required and the experience of the user.

The SkyServer (http://skyserver.fnal.gov) provides a graphical user interface to images of the sky and also enables one to download spectra of specified objects. It was primarily intended as an interface for the general public and for educational purposes, but new features are being added, making it also useful for professional astronomers. Public interest in the SDSS is illustrated by the fact that this web site has been receiving around half a million hits per month.

The MAST interface (http://archive.stsci.edu/sdss/) allows simple web-based searches around specified objects or positions on the sky. It is a useful way of retrieving SDSS observations for moderate numbers of objects in a small region of the sky.

For accessing SDSS data on large numbers of objects, and over larger areas, the SDSS query tool sdssQT is recommended. This tool allows one to query the EDR database on any measured parameters and to specify which parameters, such as position and magnitude, are to be returned. Documentation on the query tool is available from http://archive.stsci.edu/sdss/software/.

The distribution of equatorial galaxies in the EDR is shown in right ascension (RA) versus redshift wedge plots in Figure 4. The main galaxy sample is flux-limited ($r^* < 17.6$) and has a median redshift $\bar{z} \approx 0.11$. The clustering of galaxies is clearly visible in this plot: the galaxies appear to lie within filamentary structures enclosing regions of substantially lower density. The drop in galaxy density with redshift (distance from the centre of the plot) is entirely due to the fact that this sample is limited by apparent flux: only the most luminous galaxies, which are rare, can be seen beyond a redshift $z \gtrsim 0.15$.

By contrast, the luminous red galaxy (LRG) sample is designed to be volume-limited, ie. to be of uniform density, out to redshift $z = 0.38$. This sample also includes additional galaxies to $z \sim 0.5$, although these high redshift galaxies do not form a complete subsample. At $z < 0.15$, the simple linear colour cut used allows less luminous galaxies to enter the sample, hence the increase in galaxy density at these low redshifts.

The EDR includes some engineering data of sub-survey standard, and will be superseded by the first official data release, DR1, in January 2003. This release will include spectra of more than 200,000 objects over 2800 square degrees of sky. Subsequent data releases will follow at roughly yearly intervals.
Figure 4: Distribution of EDR galaxies in right ascension (RA) and redshift around the equator (declination $|\delta| < 1.25$ deg). The left plot shows 24,915 galaxies from the main flux-limited galaxy sample within a redshift $z = 0.2$. The right plot shows 8025 galaxies from the luminous red galaxy sample to $z = 0.5$.

4 Early Science Results

Although the primary science driver behind the Sloan Digital Sky Survey is characterization of the large scale structure of the Universe, the survey has already had a significant impact on several branches of astrophysics, from the investigation of asteroids in our own Solar System to the discovery of the most distant known objects in the Universe. Here I very briefly highlight some interesting results which have come out of the commissioning phase of the survey. For further details, please see the original articles as referenced.

4.1 Asteroids

Asteroids are easily detected in SDSS imaging data since they are fast-moving and very nearby (within the Solar System), leading to a significant motion relative to the background stars during the 55 s integration time. They thus appear on SDSS images as trails, the length and orientation of which enable the asteroid’s orbit to be determined. Around 13,000 asteroids have been detected in 500 deg$^2$ of SDSS commissioning data [18]. These observations have enabled an accurate determination of the size distribution of asteroids to $r^* < 21.5$ over the range 0.4–40 km. The total number of predicted asteroids with $r^* < 21.5$ is about a factor of ten smaller than that predicted by an extrapolation from previous observations of brighter asteroids ($r^* \lesssim 18$), and the number of “killer” asteroids with diameter $D > 1$ km is a factor of about three smaller than previously thought, with a new estimate of roughly one impact per 500,000 years. By completion, we estimate that the SDSS will have observed roughly 100,000 asteroids in five colours, enabling their approximate chemical
composition to be determined. There is already clear evidence for chemical segregation in the belt of asteroids between Mars and Jupiter. Asteroids in the inner part of the belt are composed mostly of rocky silicates, whereas the outer belt asteroids are primarily carbonaceous. These observations have important implications for the formation history of the Solar System.

4.2 Brown Dwarfs and Methane Dwarfs

Moving slightly further afield than the Solar System, the SDSS has also been very successful at finding brown dwarfs in the vicinity of the Sun. Brown dwarfs are sub-stellar objects which are too small to sustain thermonuclear reactions in their cores, and are thus not true stars, but are larger than planets (they are thought to be 10–70 times the mass of Jupiter). They are thus cool, below 2,500 K, and hence very red, enabling them to be easily distinguished from true stars by their colours in the SDSS filters. To date [15], SDSS has discovered around fifty new brown dwarfs, including four T-dwarfs, also known as methane dwarfs. The methane dwarfs are so cool, below 1,300 K, that their spectra are dominated by the presence of molecules such as water vapour and methane. While a methane dwarf, Gliese 229B, had already been discovered in orbit around a brighter star, the SDSS was the first survey to discover free-floating methane dwarfs. Using the discovery technique pioneered by SDSS, the Two Micron All Sky Survey (2MASS) has since found more than a dozen methane dwarfs [5]. Although very low in mass, these elusive objects may be very common, and thus may provide a significant fraction of the “dark matter” that is known to exist in the Milky Way. To understand their contribution to the total mass of the Milky Way requires determining both their abundance and their mass. The SDSS will be important in addressing both these questions, due to its capability of obtaining precision five-colour photometry over a very large area of sky.

4.3 Star Structures in the Galaxy

The SDSS has discovered an unexpectedly large number of blue stars within 20 degrees of the Galactic plane. It is thought that these stars could be part of a disrupted dwarf galaxy, or a disk-like distribution of stars that is puffier than accepted models of the stellar disk of the Galaxy, and flatter than the spherical distribution in the halo [26]. These observations suggest that the model for our Galaxy needs to be reconsidered. One possible explanation is that these star structures came from tidal disruption of nearby dwarf galaxies such as Sagittarius, since the ages and metallicities of the stars are consistent with the stellar populations in Sagittarius.

4.4 Galaxy luminosity function

The distance to a galaxy can be obtained from its spectroscopic redshift using Hubble’s law, which says that the recession velocity of a galaxy is linearly proportional to its distance. Knowing the distance to a galaxy, its intrinsic luminosity may be determined from its apparent magnitude using the inverse-square law. By calculating the maximum distance to which a galaxy of given luminosity may be seen, one can find the *galaxy luminosity function*, $\phi(L)$, the number density of galaxies as a function of intrinsic luminosity. It has long been known that the galaxy LF is well fit by the
Schechter function [30],

\[ \phi(L) \, dL = \phi^*(L/L^*)^\alpha \exp\left( -\frac{L}{L^*} \right) \, d(L/L^*), \]

in which the number density of faint galaxies is described by a power law with index \( \alpha \approx -1.2 \). For galaxies brighter than a characteristic luminosity \( L^* \), the number density drops exponentially.

We have determined the luminosity function from a sample of 11,275 galaxies in the SDSS commissioning data [3], and find that the LF is extremely well fit by a Schechter function over a range of 8 magnitudes. The use of Petrosian magnitudes by the SDSS means that a larger fraction of a galaxy’s light is being measured than is the case with most previous surveys. The integrated luminosity density of the Universe determined from SDSS measurements is thus a factor 1.5–2 times larger than previously thought. This improves the agreement with most models of galaxy formation, which predict a higher density of stellar matter than previous observational estimates.

### 4.5 Galaxy clustering

The clustering of galaxies provides a powerful probe of the initial density perturbations in the early Universe, the power spectrum of which is determined by cosmological parameters such as the matter density and Hubble parameters, \( \Omega_m \) and \( h \) respectively. On large scales, \( r \gtrsim 20 \) Mpc, the clustering of galaxies is related to the primordial density fluctuations by linear perturbation theory, but on smaller scales, non-linear effects can change the shape of the observed clustering pattern.

The clustering of galaxies is most frequently measured with the two-point correlation function \( \xi(r) \), which gives the excess probability above random of finding two galaxies at separation \( r \), or its Fourier inverse, the power spectrum \( P(k) \). The huge volume of the completed SDSS redshift survey will enable estimates of the galaxy power spectrum to \( \sim 1000 \) h\(^{-1}\) Mpc scales. Figure 5a shows the power spectrum \( P(k) \) we would expect to measure from a volume-limited sample of galaxies from the SDSS northern redshift survey, assuming Gaussian fluctuations and a \( \Omega_m h = 0.3 \) cold dark matter (CDM) model. The error bars include cosmic variance and shot noise, but not systematic errors, due, for example, to Galactic obscuration. Provided such errors can be corrected for, we can easily distinguish between \( \Omega_m h = 0.2 \), as indicated by a recent study of the masses of SDSS galaxy clusters [1], and \( \Omega_m h = 0.3 \), favoured by previous studies, as Figure 5a demonstrates. The noted systematic effects of Galactic obscuration will be minimized by SDSS observations of distant F stars, far from the Galactic centre. These stars, three of which are observed on each spectroscopic plate, have well-understood intrinsic colours, and so can be used as reliable reddening indicators. Adding the luminous red galaxy sample (Fig. 5b), will further decrease measurement errors on the largest scales, and so we also expect to be able to easily distinguish between low-density CDM and mixed dark matter (MDM) models, and models with differing shapes of the primordial fluctuation spectrum.

Given the relatively small sky coverage of our existing data, we are not yet able to place reliable constraints on cosmological parameters. We can however use observations of galaxy clustering to test the quality of our photometry and star-galaxy separation, and to investigate the relative clustering strength of different types of galaxies on small scales.
Figure 5: Left: (a) Expected 1σ uncertainty in the galaxy power spectrum $P(k)$ we would measure from a volume-limited sample from the completed SDSS northern survey, along with predictions of $P(k)$ from four variants of the low-density CDM model. Note that the models have been arbitrarily normalized to agree on small scales ($k = 0.4$); in practice the COBE observations of CMB fluctuations fix the amplitude of $P(k)$ on very large scales. Right: (b) Power spectrum expected from the luminous red galaxy sample (BRGs), assuming that these galaxies are four times as strongly clustered as the main sample galaxies.

4.5.1 Angular clustering

A series of papers [7, 9, 32, 37, 38] have studied the angular clustering of galaxies in SDSS commissioning data. These papers are based on a single survey stripe (runs 752/756 observed in March 1999) measuring $2.5 \times 90$ degrees and containing some 3 million galaxies to $r^* = 22$. Star-galaxy separation is performed using a Bayesian likelihood and approximately 30% of the area is masked out due to poor seeing [32]. The angular correlation function, $w(\theta)$, which describes the excess probability over random of finding two galaxies at angular separation $\theta$, is consistent with that measured from the APM Galaxy Survey [22] when scaled to the same depth [7].

An important test of the star-galaxy separation and of the photometric calibration is to check that $w(\theta)$ scales as expected with apparent magnitude. (We expect $w(\theta)$ to shift to smaller angular scales and a lower amplitude as we look at more distant, and hence apparently fainter, galaxies. This scaling is quantified by Limber’s equation [19].) Figure 6 shows that the scaling of $w(\theta)$ is well-described by Limber’s equation, particularly when a vacuum-dominated ($\Omega_m = 0.3, \Omega_\Lambda = 0.7$) cosmology is assumed. Further tests for possible sources of systematic errors in the SDSS data are described in detail in [32] and the angular clustering results are summarized in [7].
4.5.2 Spatial clustering

A preliminary estimate of the spatial clustering of galaxies has been made using redshift information [41]. This sample consists of 29,300 galaxies with \( r^* < 17.6 \) and within \( \pm 1.5 \) magnitudes of the characteristic magnitude \( M^*_r \) (corresponding to the characteristic luminosity \( L^* \) in the Schechter function fit to the luminosity function, see §4.4), distributed non-contiguously over 690 square degrees.

When using redshifts to infer distances, one relies on the Hubble relation, i.e. that distance is proportional to recession velocity. In fact, galaxies have peculiar velocities relative to the Hubble expansion, leading to an error in estimated distances. It is important to take these distance errors, or redshift-space distortions, into account when measuring galaxy clustering. One way of doing this is to estimate galaxy clustering as a function \( \xi_2(r_p, \pi) \) of two components of the separation vector: the line of sight separation \( \pi \), which is affected by peculiar velocities, and the sky-projected separation \( r_p \), which is not. In the absence of redshift-space distortions, the contours of \( \xi_2(r_p, \pi) \) would be symmetric about the origin, but small-scale peculiar velocities cause an elongation of the contours along the line of sight direction \( \pi \), the so-called “finger of God” effect. One can estimate a projected correlation function \( w_p(r_p) \) that is unaffected by redshift-space distortions by integrating \( \xi_2(r_p, \pi) \) along the line of sight \( \pi \),

\[
w_p(r_p) = 2 \int_0^\infty d\pi \xi_2(r_p, \pi) = 2 \int_0^\infty dy \xi(\sqrt{r_p^2 + y^2}),
\]

where the second integral relates \( w_p(r_p) \) to the spatial correlation function \( \xi(r) \).
Figure 7: Projected correlation functions $w_p(r_p)$ against projected separation $r_p$ for redshift survey galaxies subdivided by colour (left plot) and luminosity (right plot). Note that the slope of $w_p(r_p)$ increases from blue to red colour, but remains approximately constant with luminosity. From [41].

Table 1: Power-law parameters for the real-space correlation function $\xi(r) = (r/r_0)^{-\gamma}$. Units for the correlation length $r_0$ are $h^{-1}$Mpc. From [41].

<table>
<thead>
<tr>
<th>Sample</th>
<th>$r_0$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>$6.14 \pm 0.18$</td>
<td>$1.75 \pm 0.03$</td>
</tr>
<tr>
<td>Red</td>
<td>$6.78 \pm 0.23$</td>
<td>$1.86 \pm 0.03$</td>
</tr>
<tr>
<td>Blue</td>
<td>$4.02 \pm 0.25$</td>
<td>$1.41 \pm 0.04$</td>
</tr>
<tr>
<td>$M^* - 1.5$</td>
<td>$7.42 \pm 0.33$</td>
<td>$1.76 \pm 0.04$</td>
</tr>
<tr>
<td>$M^*$</td>
<td>$6.28 \pm 0.77$</td>
<td>$1.80 \pm 0.09$</td>
</tr>
<tr>
<td>$M^* + 1.5$</td>
<td>$4.72 \pm 0.44$</td>
<td>$1.86 \pm 0.06$</td>
</tr>
</tbody>
</table>

We find that $\xi(r)$ is well-fit over the range $0.1 < r < 30h^{-1}$Mpc by a power law $\xi(r) = (r/r_0)^{-\gamma}$ with parameters given in Table 1. The correlation length $r_0 = 6.14 \pm 0.18h^{-1}$Mpc is larger than $r_0 = 5.1 \pm 0.2h^{-1}$Mpc found by an earlier study [21], presumably because dwarf galaxies with $M > M^* + 1.5$ have been excluded from the SDSS analysis. The index $\gamma = 1.75 \pm 0.03$ is in very good agreement with the earlier result ($\gamma = 1.71 \pm 0.05$).

This analysis also allows one to explore the dynamics of galaxies. We find that for close pairs of galaxies, at a projected separation $r_p < 5h^{-1}$Mpc, the rms relative velocity of galaxies $\sigma \approx 600$ km/s.
Figure 8: Mass-luminosity relation in the five SDSS bands estimated from weak lensing. The inset in each panel plots estimated mass within $260h^{-1}$kpc ($M_{260}$) as a function of lens luminosity. The contours show 1, 2 and 3 sigma confidence limits on the scale factor $\Upsilon$ and the power-law index $\beta$ in the relation $M_{260} = \Upsilon(L/10^{10}L_\odot)^{\beta}$. Note that inferred mass has only very weak dependence on $u$-band luminosity, but in the redder survey bands $griz$, the mass-luminosity relation appears to be linear. From [25].

Figure 7 shows the clustering properties for two subsamples of the galaxy population selected by restframe $u-r$ colour at $(u^* - r^*)_0 = 1.8$, corresponding roughly to bulge (red) and disk (blue) dominated galaxies. The red galaxies exhibit a steeper power-law slope and longer correlation length than the blue galaxies, as indicated by the power-law fit parameters in Table 1. Also shown in Figure 7 are the correlation functions for three, volume-limited samples, with luminosities centered on $M^* - 1.5$, $M^*$ and $M^* + 1.5$ (bright, medium and faint). The power-law slopes for these samples are all consistent with $\gamma = 1.8$, although the correlation length $r_0$ decreases as expected from bright to faint luminosities.

### 4.6 Galaxy-mass correlation function

So far, I have summarized recent SDSS results concerning the distribution of luminous matter in the Universe. Direct constraints on the dark matter distribution may be obtained from gravitational lensing, in which the images of background sources are distorted by the gravitational field of foreground masses. McKay et al. [25] have made weak lensing measurements of the surface mass density contrast around foreground galaxies of known redshift. Although the lensing signal is too weak to detect about any single lens, by stacking together around 31,000 lens galaxies a clear lensing signal is detected. The galaxy-mass correlation function is well fit by a power-law of the
form $\Delta \Sigma_+ = 2.5(r/Mpc)^{-0.8}hM_\odot$ pc$^{-2}$, where $M_\odot$ represents the mass of the Sun. The strength of correlation is found to increase with the following properties of the lensing galaxy: late $\rightarrow$ early-type morphology, local density and luminosity in all bands apart from $u'$. Figure 8 shows the relationship between inferred mass within a $260h^{-1}$kpc radius and luminosity in each of the survey bands.

4.7 High-redshift quasars

The SDSS has broken the $z = 6$ redshift barrier, with the discovery of a quasar at a redshift $z = 6.28$, along with two new quasars at redshifts $z = 5.82$ and $z = 5.99$ [11]. These objects were selected as $i$-dropouts: $i^* - z^* > 2.2$ and $z^* < 20.2$. Contaminating L and T dwarfs were eliminated with followup near-IR photometry and confirming spectra were obtained with the ARC 3.5m telescope. The SDSS has now observed a well-defined sample of four luminous quasars at redshift $z > 5.8$. The Eddington luminosities of these quasars are consistent with a central black hole of mass several times $10^9$ M$_\odot$, and with host dark matter halos of mass $\sim 10^{13}$ M$_\odot$. The existence of such mass concentrations at redshifts $z \approx 6$, when the Universe was less than 1Gyr old, provides important constraints on models of formation of massive black holes. We expect to discover $\sim 27$ z $> 5.8$ quasars and one z $\approx 6.6$ quasar by the time the survey is complete. Such observations will set strong constraints on cosmological models for galaxy and quasar formation.

5 Conclusions and Acknowledgments

The Sloan Digital Sky Survey is now fully operational and is producing high quality data at a prodigious rate. We have imaged 4278 deg$^2$ of sky in five colours and have obtained more than 350,000 spectra. Much exciting science has already come out of just a small fraction of the final dataset and we look forward to many more exciting discoveries in the coming years.

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References


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