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The Sloan Digital Sky Survey: Status and Prospects

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THE SLOAN DIGITAL SKY SURVEY: STATUS AND PROSPECTS

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Abstract

The Sloan Digital Sky Survey (SDSS) is a project to definitively map π steradians of the local Universe. An array of CCD detectors used in drift-scan mode will digitally image the sky in five passbands to a limiting magnitude of $r' \sim 23$. Selected from the imaging survey, 10^6 galaxies and 10^5 quasars will be observed spectroscopically. I describe the current status of the survey, which is due to begin observations early in 1997, and its prospects for constraining models for dark matter in the Universe.

1 Introduction

Systematic surveys of the local Universe ($z \lesssim 0.2$) can provide some of the most important constraints on dark matter, particularly through the measurement of the clustering of galaxies and clusters of galaxies on large scales. Most existing galaxy and cluster catalogues are based on photographic plates [7, 3], and there is growing concern that such surveys might suffer from severe surface-brightness selection effects, so that they are missing a substantial fraction of the galaxy population. In addition, the limited volume of existing redshift surveys means that even low-order clustering statistics, such as the galaxy two-point correlation function, cannot reliably be measured on scales beyond $100h^{-1}\text{Mpc}$, an order of magnitude below the scale on which COBE has measured fluctuations in the microwave background radiation.

A collaboration has therefore been formed with the aim of constructing a definitive map of the local universe, incorporating digital CCD imaging over a large area in several passbands and 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 collaboration comprises around 100 astronomers and engineers from University of Chicago, Fermilab, Princeton University, Institute for Advanced Study, Johns Hopkins University, US Naval Observatory, University of Washington and the JPG—a group of astronomers in Japan. The total cost of the survey is around \$30 million, and funding sources include the Alfred P. Sloan Foundation, the National Science Foundation and the participating institutions.

2 Survey Overview

The survey site is Apache Point Observatory, New Mexico, at 2800 metres elevation. While better sites probably exist in Chile and atop Mauna Kea, for a survey with such state-of-the-art instrumentation and significant on-site manpower requirements (eg. fibre plugging and changing spectroscopic plates), it was decided to use a site within mainland USA and with good communications and existing infrastructure.

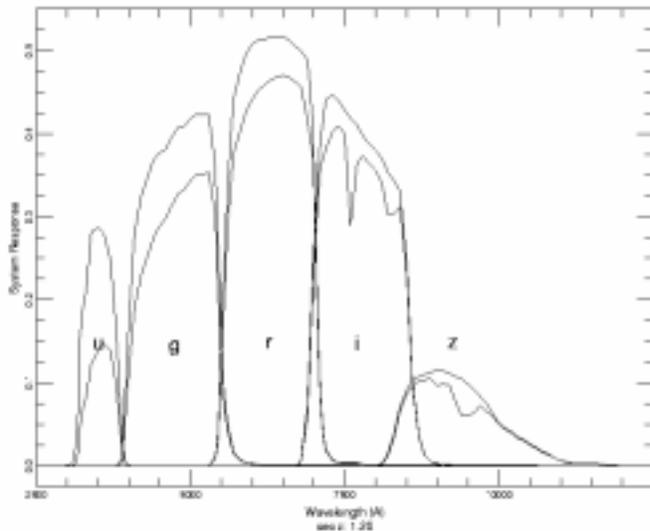


Figure 1: SDSS system response curves, with (lower) and without (upper) atmospheric extinction.

The survey hardware comprises the main 2.5-metre telescope, equipped with CCD imaging camera and multi-fibre spectrographs, a 0.6-metre monitor telescope and a 10μ all-sky camera. On the best nights (new moon, photometric, sub-arcsecond seeing) the 2.5-metre telescope will operate in imaging mode, drift scanning the sky at sidereal rate, and obtaining nearly simultaneously images in the five survey bands u' , g' , r' , i' and z' . The system response curves through the five filters are shown in Figure 1. On sub-optimal nights, which will comprise the bulk of observing time, the imaging camera will be replaced with a spectroscopic fibre plug-plate. It is planned that imaging data will be reduced and calibrated, spectroscopic targets selected, and plates drilled within the one-month lunar cycle, so that we will be obtaining spectra of objects that were imaged the previous month. We will spend most of the time observing within a contiguous π steradian area in the north Galactic cap (NGC). For those times when the NGC is unavailable, about one third of the time, we will repeatedly observe three southern stripes, nominally centred at RA $\alpha = 5^\circ$, and with central declinations of $\delta = +15^\circ$, 0° and -10° . The nominal location of survey scans is shown in Figure 2.

In the remainder of this section I discuss the various components of the survey in more detail.

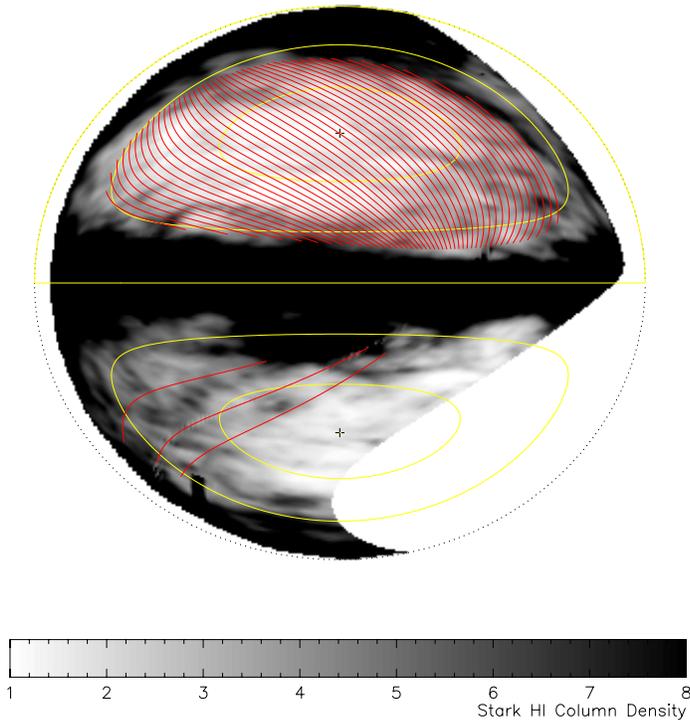


Figure 2: Whole sky plot showing the location of SDSS scans. The light lines show galactic latitudes of $b = 0, \pm 30$ and $\pm 60^\circ$, with the north and south Galactic poles being the upper and lower crosses respectively. The Galactic plane runs horizontally through the middle of the plot and the grey scale map shows Stark HI contours in units of 10^{20} cm^{-2} . The dark lines show the survey scan-lines, all of which follow great circles. We observe a contiguous area of $\pi \text{ sr}$ in the north, and three separated stripes in the south. Note that the northern survey is tilted with respect to the $b = +30^\circ$ contour to avoid regions of high HI column density.

2.5-metre telescope. The main 2.5-metre telescope is of modified Richey-Chretien design with a 3° field of view, and is optimised for both a wide-area imaging survey and a multi-fibre spectroscopic survey of galaxies to $r' \sim 18$. One of the most unusual aspects of the telescope is its enclosure. Rather than sitting inside a dome, as is the case with conventional optical telescopes, the enclosure is a rectangular frame structure mounted on wheels, which is rolled away from the telescope in order to take observations. By completely removing the enclosure from the telescope, we can avoid the substantial degradation to image quality due to dome seeing. The telescope is situated on a pier overlooking a steep dropoff so that the prevailing wind will flow smoothly over the telescope in a laminar flow, which will also help to ensure good image quality. A wind baffle closely surrounds the telescope, and is independently mounted and driven. This baffle serves to protect the telescope from stray light as well as from wind buffeting.

Imaging Camera. In order to image a large area of sky in a short time, we are building an imaging camera (Fig. 3) that contains 30×2048^2 CCDs, arranged in six columns. Each column occupies its own dewar and contains one chip in each of the five filters. Pixel size is $0.4''$. The camera operates in drift-scan mode: a star or galaxy image drifts down the column through the five filters, spending about 55 seconds in each. This mode of observing has two significant advantages over conventional tracking mode. 1) It makes extremely efficient use of observing time, since there is no overhead between exposures: on a good night we can open the shutter, drift-scan for eight hours and then close the shutter. 2) Since each image traverses a whole column of pixels on each CCD, flat-fielding becomes a one-dimensional problem, and so can be done to lower surface-brightness limits than with tracking mode images. This, along with the high quantum efficiency of modern CCDs, will enable us to detect galaxies of much lower surface brightness than can wide-field photographic surveys. There is a gap between each column of CCDs, but this gap is slightly smaller than the width of the light-sensitive area of the

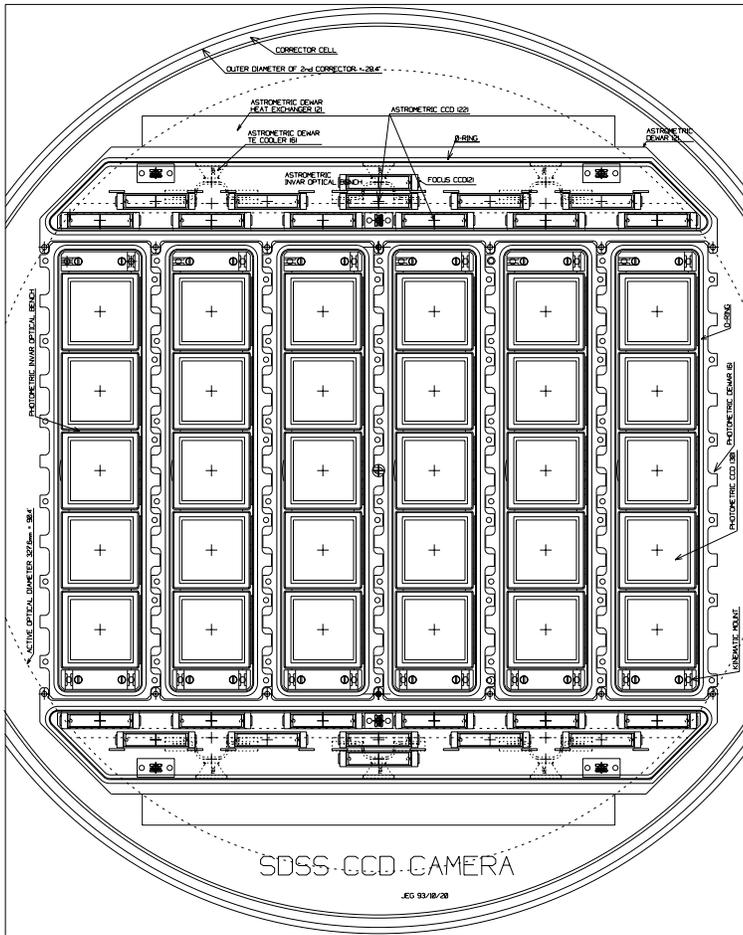


Figure 3: Focal plane layout of the SDSS CCD imaging camera, showing the 30 photometric and 24 astrometric/focus CCDs.

CCDs, and so having observed six narrow strips of sky one night, we can observe an interleaving set of strips a later night, and thus build up a large contiguous area of sky. The northern survey comprises 45 pairs of interleaving great circle scans, and so imaging observations for the north will require the equivalent of 90 full photometric nights. The camera also includes 24 smaller CCDs arranged above and below the photometric columns. These extra CCDs, equipped with neutral density filters, are used for astrometric calibration, as most astrometric standards will saturate on the photometric CCDs. Thus the photometric data can be tied to the fundamental astrometric reference frames defined by bright stars.

Spectrographs. The 2.5-metre telescope will also be equipped with a pair of fibre-fed, dual-beam spectrographs, each with two cameras, two gratings and two 2048^2 CCD detectors. The blue channel will cover the wavelength range 3900–6100 Å and the red channel 5900–9100 Å and both will have a spectral resolving power $\lambda/\Delta\lambda \approx 1800$. The fibres are 3" in diameter and the two spectrographs each hold 320 fibres. Rather than employing robotic fibre positioners to place the fibres in the focal plane, we will instead drill aluminium plates for each spectroscopic field and plug the fibres by hand. We plan on spectroscopic exposure times of 45 minutes and allow 15 minutes overhead per fibre plate. On a clear winter's night we can thus obtain 8 plates \times 640 fibres = 5120 spectra. In order to allow such rapid turnaround time between exposures we plan to purchase 8 sets of fibre harnesses, so that each plate can be plugged with fibres during the day. It will not be necessary to plug each fibre in any particular hole, as a fibre mapping system has been built which will automatically map fibre number onto position in the focal plane after the plate has been plugged. This should considerably ease the job of the fibre pluggers, and we expect that it will take well under one hour to plug each plate.

Monitor telescope. In order to check that observing conditions are photometric, and to

tie imaging observations to a set of primary photometric standards, we are also employing a monitor telescope. While the 2.5-metre telescope is drift-scanning the sky, the 0.6-metre monitor telescope, situated close by, will interleave observations of standard stars with calibration patches in the area of sky being scanned. Operation of this telescope will be completely automated, and each hour will observe three calibration patches plus standard stars in all five colours.

10 μ all-sky camera. As an additional check on observing conditions, a 10 μ infrared camera will survey the entire sky every 10 minutes or so. Light cirrus, which is very hard to see on a dark night, is bright at 10 μ , and so this camera will provide rapid warning of increasing cloud cover, thus enabling us to switch to spectroscopic observing rather than taking non-photometric imaging data.

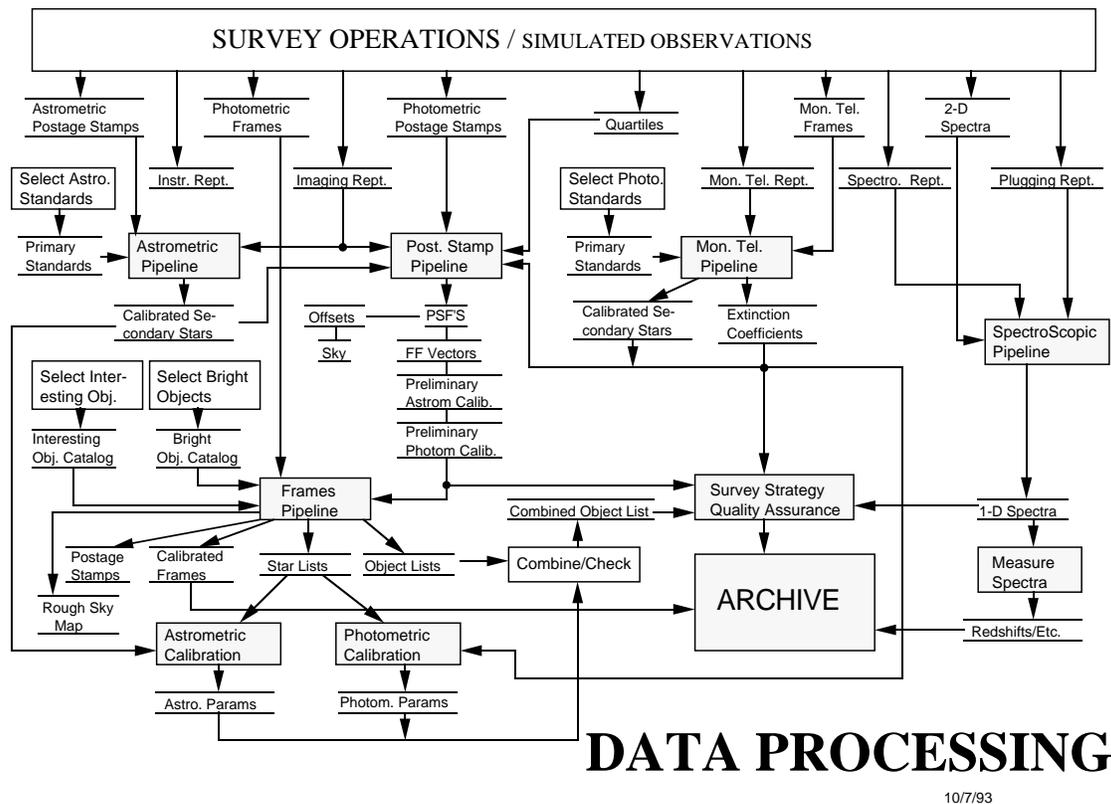


Figure 4: Top-level data processing diagram.

Data-reduction pipelines. The last, but by no means least, component of the survey is a suite of automated data-reduction pipelines (Fig. 4), which will read DLT tapes mailed to Fermilab from the mountain and yield reduced and calibrated data with the minimum of human intervention. Such software is very necessary when one considers that the imaging camera will produce data at the rate of around 31 Gbytes per hour! A “production system” has been specced and purchased that can keep up with such a data rate (bearing in mind that imaging will take place only under the best conditions, on average around two full nights per month), and consists of two Digital Alphaserver 8200 5/300s, each with 1 GByte of memory.

Pipelines exist to reduce each source of data from the mountain (photometric frames and “postage stamps”, astrometric frames, monitor telescope frames and 2-D spectra) as well as to perform tasks such as spectroscopic target selection and “adaptive tiling” to work out the optimal placing of spectroscopic field centres to maximize the number of spectra obtained. The

pipelines are integrated into a purpose-written environment known as SHIVA (Survey Human Interface and VisualizAtion environment, also the Hindu god of destruction) and the reduced data will be written into an object-oriented database.

3 Data Products

The raw imaging data in five colours for the π steradians of the northern sky will occupy about 14 Tbytes, but it is expected that very few projects will need to access the raw data, which will probably be stored only on magnetic tape. Since most of the sky is blank to $r' \sim 23$, all detected images can be stored, using suitable compression, in around 200 Gbytes, and it is expected that these “atlas images” can be kept on spinning disc. The photometric reduction pipeline will measure a set of parameters for each image, and it is estimated that the parameter lists for all objects will occupy ~ 100 Gbyte. The parameter lists for the spectroscopic sample will probably fit into 1–2 Gb, and the spectra themselves will occupy ~ 20 Gb. Work is progressing well on an astronomer-friendly interface to the database, which will answer such queries as “Return all galaxies with $(g' - r') < 0.5$ and within 30 arcminutes of this quasar”, etc.

3.1 Spectroscopic Samples

The spectroscopic sample is divided into several classes. 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 will spend a considerable time (maybe one 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, $r' \lesssim 18$. 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 $r' \lesssim 19.5$. Given photometry in the five survey bands, redshifts can be estimated for the reddest galaxies to $\Delta z \approx 0.02$ or better [4], 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 the evolution of galaxies.

Quasar candidates will be selected by making cuts in multi-colour space and from the FIRST radio catalogue [1], with the aim of observing $\sim 100,000$ quasars. This sample will be orders of magnitude larger than any existing quasar catalogues, 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.

4 Current Status

In this section I discuss the status (as of April 1996) of the various systems within the survey.

The **monitor telescope** has been operational now for several months, and is routinely operated remotely from Chicago. It is equipped with a set of SDSS filters, and is being used to observe candidate primary photometric standard stars, as well as known quasars to see where they lie in the SDSS colour system [8].



Figure 5: Photograph of the 2.5-metre telescope structure, taken shortly after installation, on 10 October 1995. Part of the telescope enclosure, in its rolled back position, appears in the bottom-left of this picture. Note that neither the mirrors nor the wind baffle are installed yet.

The **2.5-metre telescope** structure was installed on the mountaintop in October 1995 (see Fig. 5). Work is currently underway on the control systems for the telescope. Telescope **optics** are all due to be ready by June 1996. These include the primary and secondary mirrors and various corrector elements.

We possess all of the CCDs for the **imaging camera**, which is under construction at Princeton. Delivery to the mountain is expected by September 1996. Construction of the **spectrographs** is well underway, with the optics installed for one of the spectrograph cameras.

Each of the data reduction-pipelines is now basically working, with ongoing work on minor bug-fixes, speed-ups and integration of the entire data processing system. The photometric reduction pipeline is being tested using both simulated data and with data taken using the Fermilab drift scan camera on the ARC 3.5-metre telescope at the same site. Similar tests are being carried out on the spectroscopic reduction pipeline, and our ability to efficiently place fibres on a clustered distribution of galaxies is being tested using the APM galaxy catalogue [7].

The currently-projected survey schedule is as follows:

| | |
|----------------|--|
| September 1996 | Optics to be installed on 2.5-metre telescope. |
| Autumn 1996 | Imager and spectrograph commissioning. |
| Winter 1996 | Astronomical first light. |
| Early 1997 | Test period begins. |
| 1998–2003 | Survey proper carried out. |
| 2002 | First two years of survey data become public. |
| 2005 | Complete survey data become public. |

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.

5 Prospects for constraining dark matter

Since one of the topics of this meeting is dark matter, I will highlight two of the areas in which the SDSS will provide valuable data for constraining dark matter.

5.1 Measurement of the Fluctuation Spectrum

The huge volume of the SDSS redshift survey will enable estimates of the galaxy power spectrum to $\sim 1000h^{-1}\text{Mpc}$ scales. Figure 6 shows the power spectrum $P(k)$ we would expect to measure from a volume-limited (to M^*) sample of galaxies from the SDSS northern redshift survey, assuming Gaussian fluctuations and a $\Omega h = 0.3$ 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, (and star colours in the Sloan survey will provide our best *a posteriori* estimate of galactic obscuration), then the figure shows that we can easily distinguish between $\Omega h = 0.2$ and $\Omega h = 0.3$ models, just using the northern main galaxy sample. Adding the southern stripe data, and the luminous red galaxy sample, 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 MDM models, and models with differing indices n for the shape of the primordial fluctuation spectrum.

5.2 Cosmological Density Parameter

By measuring the distortions introduced by streaming motions into redshift-space measures of galaxy clustering, one can constrain the parameter $\beta = \Omega^{0.6}/b$, where Ω is the cosmological density parameter and b is the bias factor relating fluctuations in galaxy number density to fluctuations in the underlying mass distribution. While existing redshift surveys, eg. IRAS [2] and Stromlo-APM [6], are hinting that $\beta < 1$ (ie. that galaxies are significantly biased tracers of mass or that $\Omega < 1$), their volumes are too small to measure galaxy clustering in the fully linear regime reliably enough to measure β to much better than 50% or so. With the SDSS redshift survey, we expect to be able to constrain β to 10% or better.

There are several ways we might hope to determine the galaxy bias factor b . By measuring galaxy clustering on $\sim 1000h^{-1}\text{Mpc}$ scales as shown in Figure 6, we can compare with the COBE microwave background fluctuations directly, and so constrain large-scale galaxy bias in

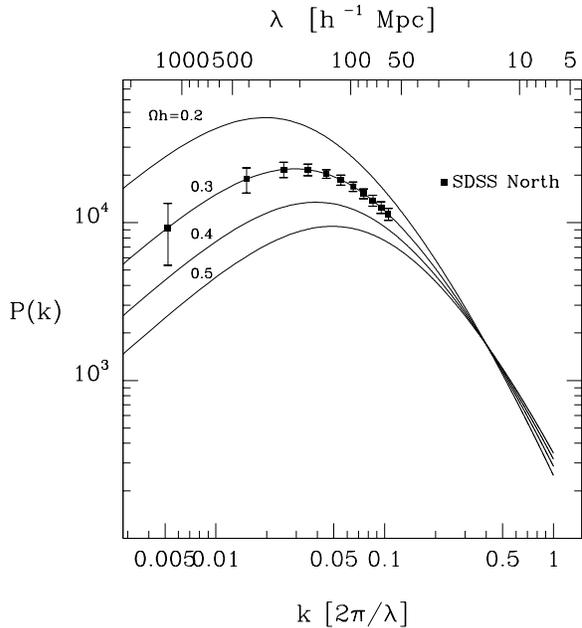


Figure 6: Expected 1σ uncertainty in the galaxy power spectrum measured from a volume-limited sample from the SDSS northern survey, along with predictions of $P(k)$ from four variants of the low-density CDM model. Note that the models have been arbitrarily normalised to agree on small scales ($k = 0.4$); in practice the COBE observations of CMB fluctuations fix the amplitude of $P(k)$ on very large scales.

a model-independent way. Analysis of higher-order clustering statistics [5], and of non-linear dynamical effects [2] will also set constraints on galaxy bias. Knowing β and b , we will be in a good position to reliably measure the cosmological density parameter Ω independent of models for the shape of the fluctuation spectrum.

6 Conclusions

It is probably no exaggeration to claim that the Sloan Digital Sky Survey will revolutionize the field of large scale structure. Certainly we can expect to rule out large numbers of presently viable cosmological models, as illustrated in Figure 6. As well as measuring redshifts for a carefully controlled sample of 10^6 galaxies and 10^5 quasars, the survey will also provide high quality imaging data for about 100 times as many extragalactic objects, from which one can obtain colour and morphological information. In addition to measuring the basic cosmological parameters Ω and h discussed in the preceding section, the SDSS will also allow us to measure the properties of galaxies as a function of their colour, morphology and environment, providing valuable clues to the process of galaxy formation.

Finally, I cannot resist the temptation to give a visual impression of what we might expect to see with the SDSS redshift survey. Figure 7 shows the distribution of 62,295 galaxies in a 6° slice from a simulation carried out by Changbom Park, assuming a low-density CDM model. This slice represents just *one sixteenth* of the million galaxy redshifts we will be measuring with the Sloan survey. I leave it to the readers imagination to dream up all the projects they would love to carry out given such a data-set.

The work described here has been carried out by many people throughout the SDSS collaboration, and I thank all my colleagues warmly. I am particularly grateful to Chris Stoughton and Michael Vogeley for providing Figures 2 and Figure 6 respectively, and to Philippe Canal for translating the Abstract into French. My attendance at the meeting was supported by a generous grant from the EEC.

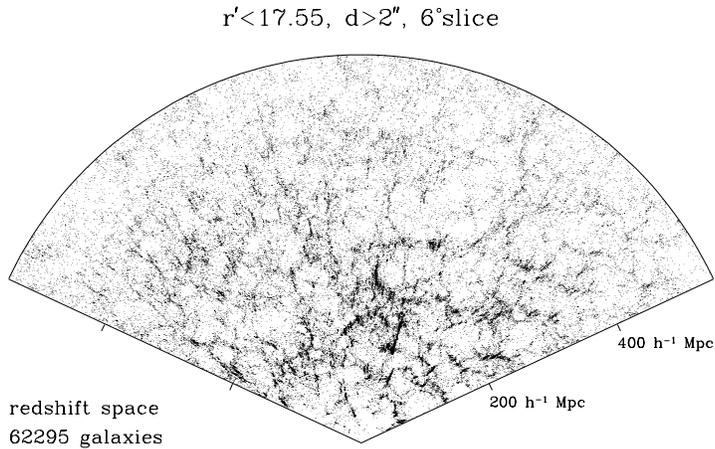


Figure 7: Redshift-space distribution of galaxies in a 6° slice from a large, low-density CDM N -body simulation generated by Changbom Park.

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LE SLOAN DIGITAL SKY SURVEY: L'ÉTAT ET CES PERSPECTIVES

Le Sloan Digital Sky Survey (SDSS) à pour but de cartographié π steradians de l'univers local. Une matrice de dispositif à transfert de charges (CCD) scannant en mode balayage produira une image digitalisée du ciel avec cinq différents filtres et avec une précision allant jusqu'à à peu près magnitude 23. Une étude spectroscopique sera faite sur une sélection de 10^6 galaxies et 10^5 quasars. Dans cet article, après avoir décrit l'état d'avancement du projet qui doit commencer à faire des observations des le début de l'année 1997, je présente ces perspectives pour l'établissement de modèles de la matière noire dans l'univers.