PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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The Sloan Digital Sky Survey

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THE ROYAL SOCIETY

The Sloan Digital Sky Survey

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The Sloan Digital Sky Survey is an ambitious multi-institutional project to create a huge digital imaging and spectroscopic data bank of 25% of the celestial sphere, approximately 10 000 deg^2 centred on the north galactic polar cap. The photometric atlas will be in five specially chosen colours, covering the π sr of the Survey area to a limiting magnitude of $r' \sim 23.1$, on $0''.4$ pixels, resulting in a 1 Tpixel map. This database will be automatically analysed to catalogue the photometric and astrometric properties of 10^8 stellar images, 10^8 galaxies and 10^6 colour-selected QSO candidates; the galaxy data will, in addition, include detailed morphological data. The photometric data are used to autonomously and homogeneously select objects for the spectroscopic survey, which will include spectra of 10^6 galaxies, 10^5 QSOs and 10^5 unusual stars. Although the project was originally motivated by the desire to study 'large-scale structure', we anticipate that these data will impact on virtually every field of astronomy, from Earth-crossing asteroids to QSOs at $z > 6$. In particular, the *ca.* 12 Tbyte multi-colour precision-calibrated imaging archive should be a world resource for many decades of the next century.

Keywords: quasi-stellar objects; archive; surveys; photometric redshifts; multi-object spectroscopy; large-scale structure

1. Introduction

The Sloan Digital Sky Survey (SDSS) is arguably the most ambitious digital database of the celestial sphere yet undertaken. It employs a special purpose 2.5 m telescope, an unusually large camera and a pair of multi-fibre spectrographs located on Apache Point, NM. Construction of all hardware and most of the software is now complete, and observations of numerous primary and secondary standard stars to underlie the specialized photometric system are underway. First light on the unique mosaic camera, the most complex astronomical imaging instrument yet constructed, occurred in May 1998. After a commissioning period of 6–12 months, we hope to be obtaining 'survey-quality' data, and it should require 5–6 years thereafter to complete the entire effort.

The title of the survey commemorates the generous financial support of the Alfred P. Sloan Foundation, a philanthropic foundation located in New York. To date, considerable additional financial support has been provided by the US Department of Energy, the Japanese Participation Group, the member universities, the US Naval Observatory and the US National Science Foundation.

† On behalf of the entire scientific and technical team of the Survey, including personnel at the Institute for Advanced Study, Johns Hopkins University, Princeton University, University of Chicago, University of Washington, Fermi National Accelerator Laboratory, the Japanese Participation Group, the US Naval Observatory, and several individuals at external institutions.

Participants in the construction and data-taking phases of the SDSS are from a dozen institutions listed in the cover page footnote. The umbrella organization to execute this project is the Astrophysical Research Consortium (ARC), a non-profit corporation of seven US educational institutions incorporated in 1984 to construct and operate astronomical facilities for its members. ARC also operates a 3.5 m general purpose telescope on the same site at Apache Point. Although not all ARC member institutions participate in both SDSS and the 3.5 m projects, the synergy of the two telescopes is clear, as the 3.5 m telescope can spectroscopically reach essentially every object imaged by SDSS, while the SDSS spectra cover only the brightest tip of the SDSS imaging archive.

Some excellent and only slightly dated review articles on the SDSS have been presented by Gunn & Knapp (1993), Gunn & Weinberg (1995) and Fukugita (1998), and a summary suitable for the general public may be found in Knapp (1997). Here, I will concentrate on an overview of the concepts of the survey and the unique contributions that we believe it will make to astronomy in general and 'large-scale structure' (LSS) in particular. However, a recurring theme of this paper will be that LSS is only a small fraction of the total scientific import of SDSS.

2. Concept and approach

(*a*) *Scientific goals*

As noted above, the SDSS is actually two surveys: one photometric and the other spectroscopic. Although objects for the spectroscopic survey are autonomously and homogeneously selected from the photometric data, both of these databases serve multiple purposes. The imaging database may broadly be said to serve four functions:

1. automated, homogeneous and quantifiable target selection and astrometry for the spectroscopic survey, based on colour and morphology of images that meet pre-selected criteria for a multitude of different scientific projects;
2. *photometric* redshifts, accurate to $\Delta z \sim 0.05$, will be available for more than 10^7 galaxies, by virtue of the carefully selected five colour bands of the survey;
3. a discovery catalogue of 10^6 QSO candidates, virtually unbiased by redshift, and with high purity; more than 60% of these objects should prove to be actual QSOs when verified spectroscopically, although we intend to obtain spectra of 'only' 10^5 of them;

and, at least in my personal view, most important of all,

4. a permanent, public, well-calibrated archive of 10^8 stellar objects and 10^8 galaxies, including five-colour photometric, astrometric and morphological data for each entry.

The spectroscopic database is likewise multifunctional, including

(i) 10^6 homogeneous galaxy spectra from an exceptionally well-characterized sample, for LSS as well as for other studies;

(ii) 10^5 homogeneous QSO spectra, which should span $0 < z < 7$ (if there are any objects at $z > 6$!) with minimal bias in z; and

(iii) 10^5 unusual stellar objects, selected autonomously for spectroscopy due to their abnormal position in five-colour space with respect to the normal stellar locus.

The imaging and spectroscopic observations are interleaved during the five-year survey; at least in principle, spectroscopy can occur in the next lunar cycle following the imaging of the target field. This protocol takes best advantage of changing sky and Moon conditions, especially given the disparate exposure times for imaging versus spectroscopy, and significantly shortens the total duration of the survey. It does, however, place severe demands on the complex software pipeline that acquires the data, performs image recognition, classification, astrometry and precision, calibrated photometry, followed by target selection for a myriad of different scientific projects. This large system must work not only reliably but *rapidly* on a huge volume of data, if the insatiable demand for new spectroscopic targets, sometimes as many as 6000 per night, is to be continually satisfied on only a few weeks of lead time.

(*b*) *Hardware*

The hardware to complete the survey is as unique as the scientific goals. The alt-az telescope is a special-purpose wide-field instrument, with a 2.5 m aperture, designed and optimized specifically for this task, although much of its heritage may be traced back to the ARC 3.5 m telescope. Both instruments are located on Apache Point, NM, a 2780 m peak located 2 km from Sunspot, NM, the site of the National Solar Observatory. Although the telescope is of conventional Cassegrain design, the 1.1 m secondary mirror yields an unusual 3° field of view at the f/5 focus where both imaging and spectroscopy are conducted; the plate-scale there is 61 μm arcsec^{-1}. The large focal plane is nearly a Mercator projection of the sky, and the optics deliver excellent images from 0.3 to 1.0 μm over this very large field. The telescope, primary and secondary optics were fabricated by L&F Industries, University of Arizona Optical Sciences Centre and Steward Observatory Mirror Laboratory, respectively, under contract to the University of Washington.

The enclosure design by M3 Engineering is also unconventional, in that to minimize both equilibration times with the environment and building-induced seeing degradation, the small building that covers the telescope during the daytime and in inclement weather is retracted on rails during observations, leaving the telescope entirely exposed during data acquisition. The telescope is then protected from wind shake by a baffle that cocoons it, and co-rotates but does not touch the instrument. This fast (f/2.2 at primary) telescope is quite small and thus stiff in any case. A second dedicated telescope of 0.5 m aperture, used for exhaustive absolute photometric calibration each night, is located nearby.

The heart of the hardware, and perhaps its most technically ambitious component, is the photometric camera (Gunn *et al.* 1998). Despite recent and rapid advances in the technology of charge-coupled devices (CCDs), it is a daunting task to cover the physically very large focal plane (650 mm) with detectors; yet only with the large 3° field can one hope to cover the 10^4 deg^2 desired for the survey in a reasonable time interval. The camera thus contains 30 CCDs, each of 2048×2048 24 μm pixels, yielding a respectable scale on the sky of $0''.4$ pixel^{-1}. At our desired limiting magnitudes and high galactic latitudes of the survey region (chosen in part to avoid large uncertainties of extinction corrections), source confusion is thus not a major problem. The CCDs, tilted to best map out the large focal plane, are housed in six separate

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

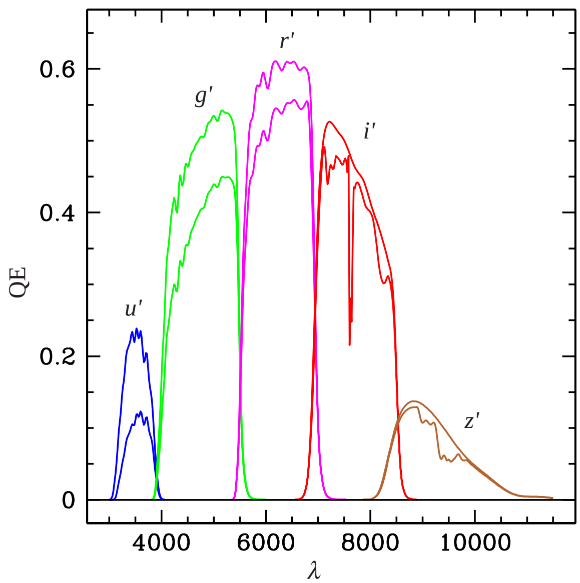

Figure 1. The expected quantum efficiency of each survey bandpass, including allowance for optics, filters and detectors (Gunn *et al*. 1998). The upper curve is 'above the atmosphere', and the lower curve includes 1.2 airmasses of atmospheric extinction.

and almost contiguous dewars, each containing five chips, one for each of the five colour bands of the survey. In normal survey operations, imaging data are acquired via TDI (time delay and integrate) mode, with charge continually clocked down the chips and read out at the same rate that the sky drifts past the focal plane. The effective integration time on any given point on the celestial sphere is 55 s, which yields reasonably faint limiting magnitudes (e.g. $r' = 23$) with a 2.5 m telescope and these highly efficient detectors. An alternative 'staring' mode to obtain images would entail very substantial inefficiencies due to the dead times while the more than 10^8 pixels in the focal plane are read out. The camera also includes on its perimeter 22 additional 2048×400 pixel CCDs of lesser sensitivity, to observe transits of brighter stars without saturation, and thus provides excellent astrometric solutions for the fainter data. This remarkable instrument was designed and constructed at the Princeton University Observatory, with the CCDs supplied by Scientific Imaging Technologies. In the wavelength regions where it is possible to use thinned back-side illuminated chips with the most favourable coatings (three of the five bands), the quantum efficiency of these excellent detectors is *ca.* 80%.

The SDSS's photometric system (Fukugita *et al*. 1996), comprised of five largely disjoint bands centred from 3500 to 9500 Å, although derived from the Gunn–Thuan system, is also distinct to this project. The survey bandpasses are shown in figure 1, and are derived from a number of constraints and compromises. The rationale to establish a new and unique photometric system should be compelling, and we believe that this is indeed the case. The SDSS's bands provide wide total coverage almost from the UV-atmospheric cut-off to the near-IR silicon cut-off, are nearly uniformly logarithmically spaced in wavelength, effectively exclude the λ5577 night-sky emission, and are well-suited to surprisingly accurate determination of photometric galaxy redshifts for a large range of z. The u' band fits nicely between the atmospheric cut-off and the Balmer jump, the g' and r' bands are reasonable matches to the J and F plates of the new Palomar Observatory Sky Survey, and i' ends just shortward of the bright OH night-sky emission. The z' band is well suited for discovery of objects beyond the current distance record of $z \sim 5$, as continuum absorption shortward of Lyα then suppresses images in other of the filters, and the very strong observed Lyα emission typical of high-z QSOs is concentrated in just one band. Considerable early work, both theoretical (Newberg & Yanny 1997; Lenz *et al*. 1999) and observational (Richards *et al*. 1997; Newberg *et al*. 1999; Krisciunas *et al*. 1998) has already been invested in delineating the normal stellar locus, as well as the positions of a variety of interesting objects, in this photometric system, as this information is essential for efficient autonomous selection of large numbers of unresolved images for many of the Survey's spectroscopic programmes, as well as for transformation of SDSS magnitudes to other systems.

It was clear from the inception of the project that an ambitious multi-fibre spectrograph would be needed to reach the goal of 10^6 homogeneous galaxy spectra and 10^5 QSOs. To the desired limiting magnitude for our LSS galaxy survey, $r' \sim 18.2$, each 7 deg^2 field contains 400–500 galaxies, and thus our design has allowed for 640 fibres per field. It should be recalled that the SDSS is not a general purpose telescope or observatory, and the spectrograph is designed for one repeated homogeneous purpose with the very highest efficiency. Thus a basic philosophical decision was made not to employ robotic positioning of fibres, as has been popular with many recent multi-object spectrometers. We have instead opted, for reasons of simplicity and reliability, for what might perhaps be viewed as a step backwards in technology, namely a metal plate custom drilled for each field by a numerically controlled milling machine. The hole positions are derived from astrometric solutions of the SDSS imaging data, to position and retain 640 fibre optic cables. The 180 μm fibres subtend $3''$ on the sky, and may be spaced by as little as $55''$ before mechanical interference becomes a problem. Overlapping plates will be required to achieve the desired homogeneity of the sample. The plates and fibres are packaged and positioned by a rigid cartridge assembly that will be plugged by hand in the daytime prior to observing each night; nine identical assemblies ensure that there are ample targets to fill even a long, clear winter night, given 45 min for a typical exposure and 15 min to change cartridges. At the risk of stating the obvious, such a night yields 6000 spectra! Bookkeeping of the correspondence of a given fibre to a given hole in the aperture plate is automated, by illuminating the fibres from the spectrograph slit end and observing the resulting pattern on the plate.

This design approach has the downside of requiring procurement of a very large number of high-quality fibres, hopefully of homogeneous properties and uniformly high throughput. We have indeed succeeded at this formidable requirement, having received and tested more than 6000 fibres with a mean throughput of 92%. The system also includes dedicated fibres for guiding and sky monitoring. The fibre system has been discussed in detail by Owen *et al*. (1998).

The spectrographs themselves consist of two identical modules, each receiving the light from 320 of the fibres. The fibres are spaced by 390 μm at the slit entrance, slightly more than twice their diameter on the sky, so bleeding and scattered light between adjacent fibres should be very minimal. The spectra cover the 3900–9100 Å range with resolution $\lambda/\Delta\lambda \sim 1800$, or *ca.* 150 km s^{-1}, comparable to the velocity dispersion of a typical galaxy observed. Each spectrograph in turn has two channels,

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

with the red and blue light split by a dichroic optic onto pairs of 2048 × 2048 CCDs with 24 μm pixels, identical to the chips in the mosaic camera; the CCD electronics for the spectrographs are also identical. These instruments, designed and built at Johns Hopkins and Princeton, are very simple, with virtually no moving parts, and with a grism as the dispersing element should provide excellent throughput, greater than 30%.

(*c*) *Data handling and software*

Even a casual reader can appreciate that the large number of pixels in the mosaic camera imply that the final SDSS database must be very large, but some specific values are instructive. The camera produces 8 MB s^{-1} of data, which will total nearly 12 TB by the end of the 10^4 deg^2 survey. As the 10^6 spectra are one dimensional, that volume of raw data is 'small', about 400 GB. The data are recorded on multiple tape drives, and sent each day from the observatory by express air courier to Fermilab for routine processing and photometric calibration, using a large software package written primarily at Princeton University and Fermilab. An 'operational' database is used for automated target selection for the spectroscopic programmes, while a compressed fully calibrated 'science database', whose architecture was developed at Johns Hopkins, will be the focus of most of the analysis, both by the SDSS team and also by the general astronomical community. For example, almost all of the original information is retrievable from a set of 'atlas images,' small regions of sky around every well-detected object (as well as interesting objects catalogued at other wavelengths but undetected in SDSS), which total about 700 GB. While the raw data directly off of the CCDs will also be stored indefinitely, and in several locations, we envisage that the atlas images, together with a merged pixel map of the entire survey area, will serve the vast majority of scientific investigations. Given the rapid and continuing decrease in price for mass disk storage, it seems plausible that by the time the survey is complete, most large observatories and astronomy departments will opt to keep this version of the data online at all times.

Many astronomers do not routinely work with data volumes of this size. One rapidly appreciates that even the simplest operations ('select every object in this portion of sky with these colours and that morphology') are not practical, at least not with current and foreseeable desktop hardware, unless great care is devoted not just to the query algorithms, but to the structure of the database. We will use a hierarchically structured object-oriented database architecture, with *Objectivity*, a commercial software environment, as the basic underlying engine.

All SDSS data will be entirely public, on a schedule limited chiefly by the human resources needed to process and calibrate this very large volume of information.

3. Survey strategy

Even the seemingly straightforward task of selecting the 10^4 deg^2 survey region is in fact subtle. A region centred precisely on the North Galactic Pole and confined to $b > 30°$ does not best minimize galactic foreground extinction—a very serious issue even at low extinction levels for any magnitude-limited extragalactic survey—nor provide an optimal range of telescope zenith distances given our observatory's latitude of +33°. We have instead chosen a somewhat oblique region that spans 130° E/W and

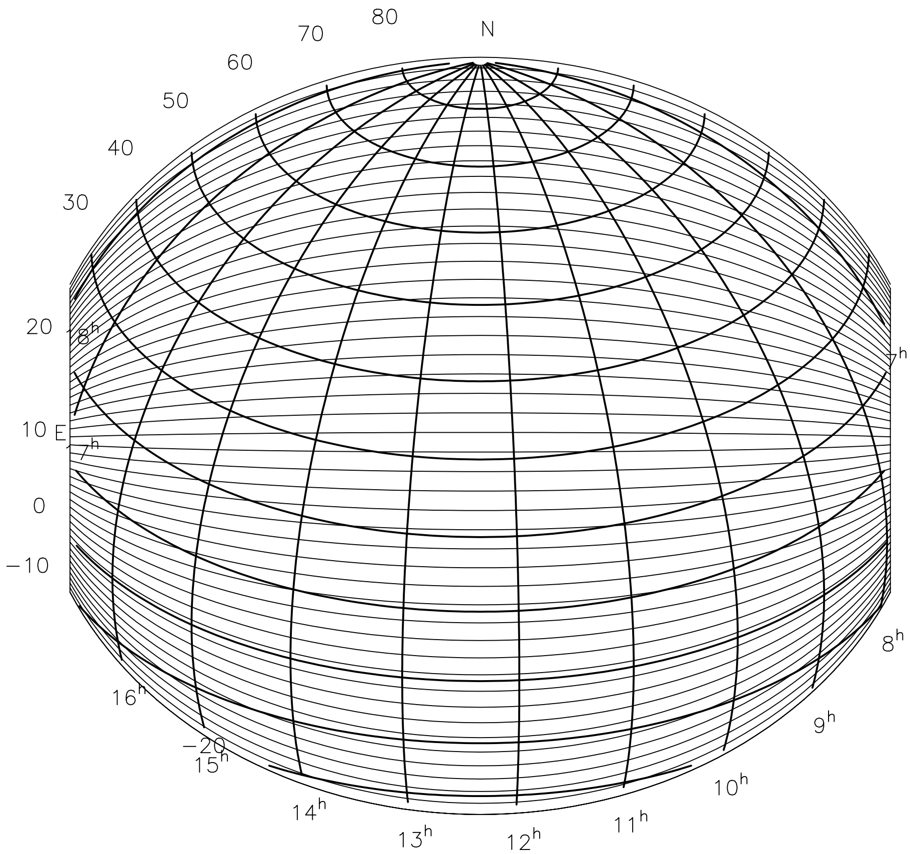

Figure 2. The 10^4 deg^2 survey region of the Sloan Digital Sky Survey.

110° N/S, centred at $\alpha = 12^{\rm h}\ 20^{\rm m}$, $\delta = +32.5°$. This region is displayed in figure 2, and has also been chosen by the FIRST team for their 1400 MHz comprehensive radio survey made with the VLA in the B configuration (Becker *et al*. 1995). Thus the entire SDSS volume will also have 1 mJy (5σ) radio coverage with *ca.* 1″ accuracy positions for point sources.

An original scientific motivation for SDSS was, of course, an intensive study of LSS, and the sample of 10^6 galaxies will indeed dominate the spectroscopic portion of the project, requiring 400–500 fibres of the 640 total on each plate. This large spectroscopic data bank will reach $r' \sim 18.2$, with $\langle z \rangle \sim 0.1$ and $z_{\rm max} \sim 0.25$. We stress, however, that it is not simply the size of this sample that is of interest, but rather the excellent level at which it is characterized. We will know the morphology of each galaxy, and limiting areal magnitudes in five colours to a few hundredths' accuracy, in a strictly homogeneous system. As selection bias is the bane of extragalactic astronomy, this virtue of the SDSS sample cannot be overstated.

An ideal goal would be to probe the power spectrum on scales to 500 Mpc, yielding elegant overlap with COBE data, as well as anticipated second-generation microwave background surveys. In practice, the effects of small and irregular foreground extinction may be severe, causing spurious signals for scales of 250 Mpc or more. We will thus use the spectra of hot halo stars in each field, together with galaxy counts, nat-

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

ural hydrogen, and infrared data, to estimate the extinction in as many independent ways as possible. We may or may not reach this 500 Mpc goal, but are confident that it will be difficult to do better by any other technique. The combination of results from large surveys such as SDSS and 2dF (Colless, this issue) with upcoming microwave background measurements from MAP and Planck will be particularly exciting, with prospects for remarkably precise and reasonably model-independent determinations of H_0 and Ω (see, for example, Eisenstein *et al*. 1998; Gawiser & Silk 1998).

About 100 fibres per spectroscopic plate will be devoted to a large QSO survey. Candidates for spectroscopy are, like the galaxies, selected autonomously from the SDSS's photometric data, although in this case primarily colours rather than morphology are employed. Simulations and some limited actual data (Richards *et al*. 1997) indicate that the five SDSS photometric bands are highly efficient at identifying QSO candidates at all redshifts; only a relatively narrow band at $z \sim 2.5$, where the QSO locus passes through the normal stellar locus, is problematic. Furthermore, the spectroscopic integration times are optimized for galaxies, but clearly will yield useful results considerably fainter for QSOs, where all the light falls in the fibre, and strong emission lines permit easy redshift determination. We thus expect the SDSS to yield 10^5 spectra of (essentially all previously uncatalogued) QSOs, to a limit of $g' \sim 19.7$. This sample is 10 times larger than the sum of all QSOs currently known from all sources. Aside from the considerable value to QSO physics of such a homogeneous spectroscopic sample, with precision colours and astrometry as well, we can anticipate *ca.* 3×10^5 absorption line systems in the data bank. While our spectral resolution is less than ideal for such work, these data do provide an additional probe of LSS quite separate from the galaxy sample. Finally, large systematic searches such as the SDSS are surely the best way to identify the brightest members of any sample, in this case useful for later absorption line studies at large telescopes and from space.

Colour selection from the SDSS's imaging data will provide 10^6 additional QSO *candidates* to $i' < 21.5$ over the π sr survey region. While we have insufficient fibres to observe each, this will be a finding list of high purity (greater than 60%) for future work, and also contain some extremely high-z objects. Uncertain but reasonable extrapolations (Schneider 1998) imply that the SDSS may find *ca.* 40 objects at $z > 6$.

There will typically be several dozen fibres per spectroscopic plate remaining after the LSS galaxy and QSO spectroscopic surveys receive their allocation, even after additional fibres are used for various overheads such as sky background, guiding, photometricity monitoring, etc. These excess fibres will be used for a wide variety of scientific programmes in stellar and extragalactic astronomy, probably limited chiefly by the imagination of our team. The majority of them will be allocated autonomously via colour and morphological selection from the imaging database. (Although the capability does exist to manually specify an individual target for spectroscopic observation, the SDSS is hardly a good venue for such work; one might just as easily walk 20 m down the road and use the ARC's 3.5 m general-purpose telescope.) We will, for example, take spectra of as many objects as possible that lie far off the five-colour locus of normal stars, but for some reason have not been selected for the QSO survey, as well as objects that coincide with FIRST radio and ROSAT All Sky Survey X-ray positions. We thus expect to discover numerous unusual stars in the halo, ranging from distant carbon stars and RR Lyraes (invaluable as halo

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

dynamic probes) to cataclysmic variables and other degenerate binaries, extremely metal poor stars, planetary nebulae, dwarf carbon stars, hot white dwarfs, etc.

In the autumn months, the survey region is not accessible at our observing site, but a reasonable amount of high galactic sky near the south polar cap is available. There is little virtue in repeating the primary survey protocol during this time, as the total survey volume is not then rapidly increased. Instead we plan to perform a separate deep-imaging programme that we refer to as the 'Southern Survey' (not, however, to be confused with the Southern Hemisphere). Over the five years of the main survey, we will repeatedly image a 225 $\deg^2$ stripe in this region, on approximately 45 separate visits. The sum of these data will go *ca.* 2 mag fainter than the main survey, e.g. to $r' = 25.1$, as well as probe yet another new portion of discovery space, namely the nature of time variability of the faint high-latitude sky on a time-scale of approximately one month. These data also provide an empirical determination of the completeness of many aspects of the main survey. Various special-purpose spectroscopic programmes may also be performed here.

4. Scientific strengths of the SDSS

In a project that performs such a comprehensive survey, together with a large and disparate number of targeted investigations, ranging from Earth-crossing asteroids to $z > 6$ QSOs, it is most certainly a matter of personal taste to rank order, or even briefly but completely enumerate, the scientific strengths of the programme. Nonetheless it seems an appropriate summary to at least attempt to do so. Therefore, I list here a strictly personal view, in inverse order (from least to most important), of what I view as the scientific strengths of the SDSS.

(*a*) *Large database*

The five-year survey will produce 10^6 galaxy spectra, 10^5 QSO spectra, 10^6 QSO images, 10^8 galaxy images with more than 10^7 photometric z and 10^8 stars with five-colour photometry.

(*b*) *Homogeneity of the data*

The survey will yield 10^6 galaxies and 10^5 QSOs in the identical spectrograph with very high signal-to-noise; additionally, 10^8 galaxies and 10^8 stellar images will be catalogued with five-colour very well-standardized photometry and excellent astrometric accuracy.

(*c*) *Exceptionally well-characterized samples*

Each of the galaxies selected for the LSS survey has quantitative morphological data, and extremely accurate five-colour photometry. At the risk of stating something very well known to all LSS pundits, *LSS conclusions are known to depend on colour and morphology!* Numerous recent authors (see, for example, Loveday *et al*. 1995; Hermit *et al*. 1996; Guzzo *et al*. 1997) stress that one's knowledge of the precise composition of the galaxy sample will heavily influence one's conclusions. Even such prosaic issues as slightly inaccurate removal of minor patchy amounts of foreground extinction can play havoc with a magnitude-limited sample. Similar considerations apply to QSOs; in the SDSS they will be selected from five-colour space, with only one narrow deadband near $z \sim 2.5$. Of course, the impact of galaxy morphology on LSS is not just an annoying selection effect, but something interesting to study in its own right; it yields important inferences on the bias of galaxies relative to dark matter, and therefore on galaxy formation.

(*d*) *Science not related to LSS*

For stellar population studies, we have 10^6 galaxy spectra with the identical spectrograph, *with detailed morphology and five-colour photometry available for each object*. Large numbers of previously unrecognized clusters of galaxies, low surface brightness galaxies, and gravitational lenses will be identified. The survey will produce more than 10^5 unusual stellar spectra; there are implications not just for stellar astronomy but for galactic structure, high-latitude extinction, etc. Numerous (*ca.* 10^5) asteroids will be found and characterized photometrically, including not just main belt objects, but also near Earth objects, Centaurs, Kuiper Belt objects and long-period comets.

(*e*) *Discovery potential*

Many spectroscopic fibres are available in each field, unrelated to the LSS or QSO surveys, for objects of odd colour and/or morphology, FIRST radio sources, ROSAT All Sky Survey X-ray sources, etc. The filter system is especially well optimized for $z > 5$ QSOs.

(*f*) *Archival value of the imaging data bank*

The five-colour $0''.4$ pixel extremely well-calibrated imaging archive of the entire northern sky at $b > 30°$ will be a community resource for decades. This ambitious, but we believe correct, statement seems the most appropriate with which to conclude this review.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A