Mass-producing spectra: The SDSS spectrographic system

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ABSTRACT

The Sloan Digital Sky Survey is the largest redshift survey conducted to date, and the principal survey observations have all been conducted on the dedicated SDSS 2.5m and 0.5m telescopes at Apache Point Observatory. While the whole survey has many unique features, this article concentrates on a description of the systems surrounding the dual fibre-input spectrographs that obtain all the survey spectra and that are capable of recording 5,760 individual spectra per night on an industrial, consistent, mass-production basis. It is hoped that the successes and lessons learned will prove instructive for future large spectrographic surveys.

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1. THE START OF THE INDUSTRIAL REVOLUTION

The industrial revolution in astronomical spectroscopy, as with many revolutions, has taken some time to get up to speed. It can be traced back to the seminal work by Hill and collaborators\textsuperscript{1} on simultaneous spectroscopy of galaxies using the Medusa spectrograph with 32 targeted optical fibres on the 2.3m telescope at the Steward Observatory in the late 1970’s and early 1980’s, with which they succeeded in gathering useful spectra over wavelengths of \(\sim 3900–5500 \text{ Å}\) in 3-hour exposures. By the early 1990’s, the hand-crafted instrument of Steve Shectman and collaborators was at the forefront of the revolution, strip-mining the sky with the 128-fibre Fruit and Fiber spectrograph on a 2.5m telescope and celebrating obtaining several hundred spectra per night during the Las Campanas Redshift Survey.\textsuperscript{2–4} This was an order of magnitude improvement in observing efficiency in about a decade.

To date, some three dozen multi-object fibre spectrographs and variants have been built or proposed and the multiplex advantage of simultaneously reaping redshifts from large numbers of galaxies in each telescope field of view has remained a powerful force driving forward instrument system design. While many of the ideas introduced by Hill \textit{et al}. – e.g. drilled-plate fibre mounting, cartridge interchange, coherent bundles of fibres for imaging guide stars – remain familiar in one form or another in many of these instruments, developments in robotics have permitted several other classes of spectrograph design to appear (see e.g. Refs. 5 and 6).

Improvements in efficiency have continued so that, today, we can obtain spectra of galactic and extragalactic objects nearly an order of magnitude faster still than in the 1990’s, over a wider wavelength range and with higher spectral resolution. Although the Sloan Digital Sky Survey (SDSS) is using a 2.5m telescope, of similar size to that used by Shectman and collaborators, we have a much larger array of fibres (640 against 128), larger and more efficient detectors (\(4 \times 2048 \times 2048\) pixels on integrating CCDs against \(1 \times 2048 \times 1520\) pixels on a photon counter) that have reduced exposure times by half, and much less overhead in the observing procedures. The result is that we can observe up to 9 target fields per night now versus 4-5 then to similar limiting magnitudes, and gather 5 times more targets per field, covering wavelengths of \(\sim 3800–9100 \text{ Å}\). We have also learned how to routinely achieve a spectrophotometric calibration for fibre spectra of a few percent.\textsuperscript{7}

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Indeed, on each of the nights of MJD 52669 (2003 January 29/30) and MJD 53084 (2004 March 19/20), the SDSS observers at Apache Point Observatory (APO) obtained 5,760 spectra using the SDSS systems - possibly the most individual spectra ever observed per night so far. But there may be more to come: radical design concepts for future fibre-input spectrographs on telescopes of up to 8-m aperture, such as LAMOST and KAOS, offer the possibility of further increasing productivity by perhaps another order of magnitude in the next decade.

Details of the SDSS telescope, instruments and observing procedures have been well documented elsewhere. This article focuses on the elements that were critical to the success of the SDSS in obtaining the spectra at the best rate: efficient equipment and observing procedures; flexible observing plans; real-time quality assurance, and, most important, a highly skilled and motivated team of people.

2. EFFICIENT OBSERVATORY HARDWARE

2.1. Enclosures and thermal management

The SDSS 2.5m telescope has two separate enclosures that divide the functions of a conventional “dome” type of enclosure. The larger secondary enclosure, whose principle functions are to protect the telescope from weather

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*If anyone is aware of a larger count, please contact P.R.N.
and facilitate engineering operations, consists of a run-off building ("shed") which is moved on rails about 25 m from the telescope prior to nighttime operations. Removing the enclosure and refilling instrument-mounted liquid nitrogen dewars (necessary because the telescope dips to 6 deg altitude in the process) is relatively slow, taking \( \sim 20 \) min, but has little effect on observing efficiency unless weather conditions are changing rapidly.

This enclosure includes a powerful air-conditioning system which is actively managed with the objective of having the telescope and, in particular, the mirrors in thermal equilibrium with the expected outside air temperatures at twilight. To this end, both the primary and secondary mirrors carry a large array of thermometers, and much effort has been expended on improving the forced ventilation of the primary mirror to the point where we can easily track normal changes in air temperature with mirror-to-air temperature differences and cross-mirror gradients on the primary rarely exceeding 0.5 K during operations. The secondary mirror was found to be prone to super-cooling under clear sky and now carries a thermal shield on its rear (sky-facing) surface, so that the front-to-back temperature gradient is normally \(< 0.2\) K. Mirror temperatures (along with many other telescope hardware measurements) are archived and displayed in real-time to the observers with a sophisticated Telescope Performance Monitor system.\(^{13}\)

The much smaller primary enclosure, known as the wind baffle, protects the telescope from wind-shake and stray light (see fig. 1). This is unusual in that it is "shrink-wrapped" onto the telescope, with an average separation from the telescope of a just few centimetres. The wind baffle is moved by a separate servo system slaved to the telescope position. This provides advantages in that the enclosure matches the slew rate of the telescope (2 deg sec\(^{-1}\) in altitude and azimuth) and provides consistent and stable protection from buffeting in wind speeds in excess of 55 kph. The wind baffle also carries moveable flat-field screen petals atop the secondary mirror truss that can move into and out of the field of view in \( \sim 5 \) sec. These permit obtaining rapid in-situ flat-field and arc lamp calibration exposures as required.

### 2.2. Optical design

The SDSS 2.5-m telescope has an f/5 modified Ritchey-Chrétien optical design, albeit with a wide (3-deg) field of view,\(^{11}\) but it has at least one unusual feature in that the primary mirror can be pistoned a significant distance along the optical axis relative to the instrument mount to provide an image scale adjustable by \( \pm 0.05 \) per cent. This allows the observers to simply compensate for any mismatch between the temperature for which each aluminium plug-plate was designed and the actual temperature at the time of observation. Determination of the required scale is discussed in \( \S\)3.3 below.

### 2.3. Optical fibre mount plates

The SDSS spectrographs use nine identical cartridges each carrying 640 science fibres and 11 coherent fibre bundles for taking images of guide stars.\(^{14}\) These cartridges allow rapid change of the spectrographic fields targeted by the telescope. One end of each fibre is plugged into a drilled aluminium plate that is placed at the telescope focal surface. The other end of the science fibres terminate on a pair of pseudo-slits, each of which carry 320 fibres into the entrance apertures of the dual spectrographs. The coherent fibre bundles terminate on a block that is imaged by a separate camera used for guiding. The plug plates are drilled\(^{15}\) with the positions of targets selected from imaging data. The imager\(^{19}\) is thus an integral part of the spectrographic system, having the same field of view, detecting objects to \( \sim 2 \) magnitudes fainter than the spectrographic survey limits. The area covered by the plates will eventually tile the full survey area.\(^{16}\)

Plates typically carry \( \sim 590 \) fibres on survey targets plus \( \sim 50 \) fibres on calibration stars and blank sky, plus the 11 guide fibre bundles. Each plate takes \( \sim 70 \) min to observe (depending on sky conditions) including field acquisition, flat-field and arc calibration exposures, typically \( 3 \times 15 \) min pointed target exposures and changing the cartridge mounted on the telescope.

The SDSS expects to use \( \sim 2000 \) plates, so changing plates needs to be a consistent and efficient operation. The day after each night of spectrographic observations, the APO fibre-plugging crew, working in a support building at the end of the telescope pad, removes all fibres from the plates for which observations are complete, puts a new plate on the cartridge, inserts the fibres into the new plate, adjusts the plate profile to match the focal surface curvature and maps the correspondence between fibre and slit positions. The cartridge is then ready for more observations the next night. Adjusting the plate profile is particularly important for efficient operations,
as variation in focus and fibre telecentric angle across a plate can have large effects on the rate at which signal is accumulated.\textsuperscript{17}

A special plugging station lifts and inverts the cartridge, allowing two people to work comfortably together inserting fibres downwards into the new plates, with target fibres plugged into any hole then automatically mapped from slit-head position to plate position. This mapping is achieved by back-illuminating the fibres with a laser one at a time from the slit head and computer-processing images of the plug plate from a digital camera to identify which fibre lights up. All nine plates, 5,760 object fibres and 99 guide fibres can be replaced in $\sim 6$ hours during the day ready for the next night’s observations.

2.4. Instrument change

Instrument change, both from one spectrograph cartridge to the next and between spectroscopy and imaging, is naturally a frequent activity during SDSS night-time operations, so much careful thought has gone into making the process both fast and foolproof. The telescope has an altitude-azimuth mount with instruments necessarily carried on a driven rotator. All equipment changes are performed with the telescope pinned pointing at the zenith, and equipment is lowered and lifted with a hydraulic lift permanently mounted in the cone, so only the equipment actually being changed has to be moved to and from the telescope.

Switching spectrograph cartridges is a one-person operation. It involves simply unlatching and lowering one 150-kg cartridge with the hydraulic lift onto a dual-cartridge cart, moving the cart so the next cartridge is under the mount point, then lifting and latching the new cartridge. The typical time between issuing the command to slew to the instrument change position when exposures for one cartridge are completed and issuing the command to slew to the target field for the next cartridge is under three minutes, and rarely is it more than four minutes. Most of this time is in the slew. Standard procedure is presently to complete read-out of the last exposure for a field before starting the slew to instrument change, as there was concern about increasing electrical noise, but we have been experimenting with starting the slew as soon as read-out starts, without any apparent increase in noise in the data. This parallelism saves $\sim 2$ min per plate. The cartridge removed is then returned to the support building for plate replacement the following day.

Changing mode from spectroscopy to imaging is somewhat more complex. The imager\textsuperscript{10} is heavy, 550–570 kg depending on the contents of the secondary liquid nitrogen dewars, and is connected to the rest of the world by an umbilicus $\sim 10$ cm in diameter. Moving both of these safely make mounting and dismounting the imager a two-person operation. Again with the telescope pinned at zenith, the spectrograph cartridge is removed, then a second cart is lifted to carry away the spectrographic corrector lens (leaving a common corrector in place). When not mounted on the telescope, the imager lives in its “doghouse” that is mounted on the rotating floor on the opposite side from which spectrographic equipment is loaded (see fig. 1). Once the spectrograph cartridge is removed, the doghouse is opened and the imager cart is pulled out on rails onto the hydraulic lift which lifts it into place. The imager and spectrographic cartridges share a common set of latches, although the imager also has addition latches for the saddle that carries its liquid nitrogen supply and ancillary electronics.

Instrument change clearly involves moving and mating heavy and expensive equipment. As with all operations involving humans, especially when working against the clock, usually in the dark, and often in cold weather, any risk of damage to operator or equipment due to human error is to be avoided. For this reason, all telescope and instrument motions are heavily interlocked to, as far as is possible, prevent motions in the wrong sequence. For example, the interlocks sound an alarm if the doghouse is opened when the T-bars supporting the imager CCDs are not in the “transport” position, and they prevent motion of the lift to raise the imager unless the spectrograph corrector lens has been removed. Although it can be troublesome for the observers when interlocks unexpectedly prevent motion, they do improve confidence when the observers are trying to minimise the time taken to change instruments to maintain observing efficiency.
2.5. Support instruments for spectroscopy

There are two ancillary instruments at APO that are run in support of efficient spectrographic operations. First, we run a differential image-motion monitor (DIMM) to quantitatively estimate the true seeing independent of telescope-induced degradation of the point-spread function. This lets us make sensible decisions as to the thermal state of the mirrors and in choosing between imaging and spectroscopy. The DIMM is mounted on the end of the 2.5-m telescope pier, so it samples the actual seeing close to the main telescope.

Secondly, an infrared sky camera provides still images of whole sky every 30 sec from which rolling 30-minute movies are constructed, both of which have the current pointing of the telescope superimposed. This provides the observers with a detailed view of current and recent sky conditions, and quantitative measurements of the transparency of the sky based on the distribution of the histogram of pixel values. We use this both for general decisions about which mode of observing is most appropriate, and, particularly when imaging, to see if any isolated clouds have passed over the field of view of the telescope and to decide if the variance in transparency across the sky is small enough to declare conditions photometric.

3. EFFICIENT OBSERVING SYSTEMS AND PROCEDURES

3.1. Observing staff

There are presently nine staff at APO who rotate through SDSS observing shifts, although three have other duties that limit their night-shift time: one (S.J.K.) is largely involved in operations planning and coordination, another (D.C.L.) has responsibilities for overall quality assurance on the mountain, and a third (J.C.B.) is also an Observing Specialist on the ARC 3.5m and NMSU 1m telescopes. Our normal mode of operation is for rolling pairs of observers to staff each night shift, each person working for 2–6 nights in a row. Since early 2003, we have also operated a day shift, staffed by one of the observers in monthly rotation.

3.2. Preparation before nightfall

Efficient night-time operations begin with a working telescope and instruments. The observer on day shift is responsible for ensuring all system are operational before sunset in liaison with the APO engineers. Pre-flight checks include full operational tests of the telescopes, instruments and data acquisition systems, plus mounting the first instrument for the night and fine adjustment of the spectrographs' collimation and focus.

Although on the vast majority of nights, all systems are “go”, catching the rare problems that do come up during daylight is clearly advantageous for efficiency. In addition, stress is reduced when the night shift can be confident of being greeted with a working system (or at least one with known problems!).

Observing science targets takes place while the sun is ~12 deg or more below the horizon. When we start the night with spectroscopy, we will usually acquire the first field before the end twilight, so we can make the initial focus and image scale adjustments before dark.

3.3. Target acquisition, guiding and exposure control

Provided the pointing model and associated encoder scales are updated regularly to compensate for thermal variations, the SDSS telescope is capable of placing guide stars into (or very close to) the coherent guide fibres for any plate on command. We normally update the pointing model at the start of each dark run. The observers do not have to deal with target positions in terms of sky coordinates. Instead, the control software is told which cartridge and plate are mounted, and the sky coordinates are automatically loaded from the plate database. This avoids all transcription errors and makes target acquisition very straightforward.

Once two or more guide stars are visible in the display showing the images from the coherent fibre bundles, an autoguider takes control of all three telescope axes. This will centre the guide stars and maintain pointing to within ~0.1 arcsec with ~15 sec resolution. The autoguider also calculates and reports the required change in telescope image scale to match the plug plate temperature. This is not part of the automated loop, as there

†Live data from both instruments described here are available nightly on the APO web site, www.apo.nmsu.edu. No discussion of the SDSS 0.5m photometric telescope is included here, as its function is to support imaging operations and is hence outside the scope of this article.
is significant image motion when the primary mirror is piston to adjust the scale. However, once the observer has set the image scale, it normally remains within the permitted tolerance\(^{17}\) of ±0.003 per cent for the duration for exposures for a plate. The mirror servos automatically maintain focus during scale changes, so provided the telescope remains in thermal equilibrium, no further focus adjustment is needed from the observers when switching between plates designed for different observational temperatures.

The autoguider also reports the apparent seeing disk size measured from the guide star images, together with an estimated integration efficiency based on the known brightness of and measured flux from the guide stars. The observers can then track and compensate for focus changes and dynamically adjust exposure times to match conditions, also using information from the infrared sky camera.

We have easy-to-use tools incorporated into the guider software for finding best telescope focus by sweeping through a range of secondary mirror positions and plotting the resulting guide star image sizes at each position. A focus sweep typically takes a few minutes. On nights with stable ambient temperatures, this may only be needed at the start of night, and the observers will then use experience, helped by a simple model of the thermal characteristics of the telescope, for subsequent focus adjustments. However, on some nights the temperature varies enough to require more frequent focus sweeps with a consequent loss of observing efficiency. In efforts to find faster procedures, we have conducted two sets of experiments to date. The first was a differential focusing scheme which tried to make use of the residual error between the plug plate profiles and the true telescope focal surface to determine the direction of best focus. The second attempted a Hartmann scheme, closing half of the flat-field petals at a time to produce a lateral shift in image positions correlated with the direction of best focus. In both cases the results so far have been inconclusive.

Our aim when observing, as described in the next section, is to achieve just sufficient signal-to-noise ratio to meet survey requirements. We take at least three target exposures to allow automatic cosmic ray discrimination in the data reduction pipeline. Under the best conditions, these can be a short as 600 sec, rising to perhaps \(5 \times 1500\) sec in cloud or very poor seeing.

For much of the survey through the end of 2003, observations of each plate included a 4 min smeared exposure of the target that synthesised a larger aperture intended for spectrophotometric calibration; these have now been discontinued.\(^7\) Although the decision to not apply this calibration was based on spectrophotometric considerations,\(^{19}\) the decision to cease obtaining smears clearly influenced observing efficiency.

### 3.4. Real-time quality assurance

Data quality assurance must start at the telescope, or much time can be wasted either taking too much, too little, or simply bad data.

Our first aim is to ensure just enough photons are gathered for each target. Too few will not achieve the S/N required for the survey’s science goals, while too many wastes time exceeding those requirements. A second aim is that the observations are just sufficiently calibrated. We obtain at least one set of flat-field and arc lamp exposures for each plate to trace fibre apertures in the images and apply a wavelength calibration, but if there is too much flexure in the instruments during target exposures, more sets may be required. However, we do not want to waste time taking extra calibration exposures if they are not required.

To measure S/N and flexure and to check for saturation and many other problems in the data, we run a cut-down version of the full SDSS spectrographic reduction pipeline, known as SoS (Son of Spectro), on a fast dual-processor computer. SoS operation is event-driven, automatically giving results \(\sim 2\) minutes after the end of an exposure. It reports via web pages available immediately to observers and off-site collaboration, giving clear warnings about flexure, stray light, sky-line saturation, very bright objects and many more problems. It also provides a table showing the summed S/N from all the good-quality science exposures for a plate at canonical fibre magnitudes, and plots showing the S/N distribution by magnitude and fibre position. These help the observers make informed decisions on both achieving the quality targets and identifying and correcting problems. Problems are identified as soon as possible, which can result in big time savings. For example, it is not practical to combine science exposures from different pluggings of a plate, so if an exposure must be discarded we need to know before we can declare the plate finished and have it replaced with a new plate. Obtaining a replacement science exposure on the same night also saves unnecessary calibration exposures that would be required should observations be carried over to extra nights.
4. FLEXIBLE OBSERVING PLANS

We switch between imaging and spectroscopy as observing conditions dictate: imaging when the sky is moonless, photometric and seeing is < 2 arcsec FWHM, otherwise spectroscopy. However, within those criteria, we usually have a wide choice of the exact science targets to observe. For spectroscopy, we now hold a queue of ~ 350-400 plates at APO, of which typically ~ 100 are observable during a given lunation. Plates drilled for other seasons are held off site.

A plate database lets the observers choose which plates are to be plugged with fibres ready for the next night so we can observe at any time during the night. The database displays information that makes planning around current conditions easy. The principal information shown is the position on the sky of the target field for each plate and its observable time range. This time range is determined by the airmass limits over which the target image positions, which move because of changes in differential refraction, remain acceptably close to the fibre positions on the telescope focal surface. It hence varies from plate to plate. As there is a trade off between observed hour angle and the observable time range, plates are drilled with fibre positions centred for specific hour angles with the aim of maintaining a choice of plates available for each hour of the night.

The plate database also logs and reports any S/N acquired for each plate on preceding nights, and includes a handy ephemeris for the night giving times of twilight and Moon rise and set and the degree of illumination from the Moon at each plate’s location on the sky.

When observations for a plate are completed, instructions are sent to the plugging crew to replace the plate on that cartridge. The observers choose which new plates to mount, again based on information from the plate database, so as to maintain the ability to make spectrographic observations throughout the following night.

5. DEDICATED PEOPLE

The term dedicated is used here in two senses: first to mean that most APO staff who work on the SDSS systems work only on SDSS systems, and secondly, to say that the SDSS staff at APO are enthusiastic about the science that is coming out of their work. In particular, all of the SDSS Observers are career astronomers, most with doctorate-level education and experience, or with strong backgrounds in observational and engineering practice, and all with corresponding research interests.

Maintaining scientific motivation for the staff and hence, it is hoped, employing them for long periods, has been important because the learning curve for the SDSS systems is steep and long. Experience has shown that new observers take ~ 9–12 months to get fully up to speed on all systems. This approach has proven successful: no SDSS staff have left APO since 2000.

Among the observers, we have also put effort into developing individual areas of expertise. We recognise ~ 70 constituent systems, covering hardware, software, procedures, training, observing plans, data reduction and so on. We have split these up so that each observer concentrates on a particular set. Each observer has thus taken responsibility for understanding their set of systems, managing the recording and approval of changes to those systems via the GNATS problem reporting database (see next section), attending development meetings, writing procedures, and so on. This has proven to be a very successful division of effort, allowing each observer to specialise on areas of interest and also build trust that the other observers have taken similar charge of their own areas.

6. SUCCESSES

6.1. Improved reliability

Although not quantified here, all of the SDSS observing software and hardware systems at APO are now considerably more reliable than at the start of the survey, due to increases in the mean time between failures (MTBF) and decreases in mean time to repair (MTTR). The improvement in MTBF has come both from steadily ironing out bugs in the software and a strong engineering programme of improving telescope and instrument hardware and electronics. The decreases in MTTR are at least partly due to decreased workload on the staff responsible

Several of the SDSS engineering staff at APO may work on other site systems if time permits.
for the work, so that the backlogs of outstanding work are shorter, but much project management effort has also
gone into tracking and managing the tasks involved. All software and documentation has been managed using
the CVS version management package, which has allowed close control of collaborative development, testing and
migration.

The entire survey maintains a database (known as GNATS) to track all problems and change requests affecting
all aspects of the SDSS systems from construction through observing to data reduction pipelines and final data
distribution. To date, the database contains more than 6000 entries. It has been very noticeable that the number
of reported problems for the observing systems has diminished greatly in the last year, as has the frequency with
which software version numbers have incremented. Most new problems now are associated with down-stream
systems, indicating the project has reached a certain level of maturity.

There is no doubt that the effort involved in careful management of change has paid off. It is doubtful that
such a large collaborative effort could be successful without it.

6.2. Improved efficiency

As with all repeated tasks, practice makes perfect, and some of the observational efficiency gains since the start
of the survey have come simply from learning how to do things properly. However, we have also each worked hard
on our particular areas of expertise to, for example, remove redundant tasks and parallelise many observational
steps.

As an example, the time from finishing the last exposure on one spectrographic plate to acquiring the field
for the next has been reduced from a two-person ~ 10 min operation to a one-person ~ 4 min operation by such
changes as starting the slew to instrument change position as soon as the exposure starts to read out from the
CCDs, and by orchestrating the redesign of the instrument latch controls to reduce the distance the operator has
to move to disengage and re-engage the cartridges and to provide visual feedback on latch states. These are but
two small examples of a continuing programme of improvements to procedures and hardware that have greatly
reduced the overheads associated with actually gathering photons from the targets.

6.3. Consistent spectral quality

To date, the SDSS has obtained ~ 6 × 10^5 spectra, of which more than 3.6 × 10^5 have been publicly released.
Just ~ 0.5 per cent had insufficient S/N for secure spectral classification and radial velocity. We consider this
to be the greatest measure of our success: the SDSS is truly a factory producing high-quality spectra on an
industrial scale.

6.4. The record nights

On each of the nights of MJD 52669 (2003 January 29/30) and MJD 53084 (2004 March 19/20), APO obtained
5,760 spectra using the SDSS systems - the most possible in one night with the SDSS equipment. On those
record-setting nights, we were fortunate in that all the required conditions came together: photometric sky, no
moon, and seeing just too bad to warrant survey imaging. Although these are the only nights so far where we
have achieved a “max”, using all 9 available fibre-optic plug-plate cartridges, we have observed 8 plates (5,120
spectra) on several nights and 7 plates (4480 spectra) on many nights.

The candidates observed on MJD 52669 came from the SDSS programmes (which includes the main^20 and
luminous-red galaxy samples,^21 the quasar sample,^22 and other stellar and serendipitous samples generated by
the SDSS collaboration), plus two plates designed for associated programmes exploring photometric redshifts
and stellar kinematics. On MJD 53084, all the plates were from the SDSS programmes. The different classes of
objects observed on each record night are listed in table 1.

Of course, sky conditions, moon phase and variations in the length of the night with season have a big
influence on the observing rate we can achieve, making it difficult to quote meaningful average rates. However,
in typical conditions that are not good enough for imaging, we estimate our median spectrographic observing
rate at 6 plates (3840 spectra) per night.
Table 1. Candidates observed on the record-setting nights.

| MJD  | Plate | Programme   | Galaxies | Quasars | Stars | Calibration | Sky | Others |
|------|-------|-------------|----------|---------|-------|-------------|-----|--------|
| 52669| 811   | Photo-z     | 575      | 0       | 0     | 17          | 48  | 0      |
| 848  | SDSS  | 486         | 64       | 20      | 18    | 32          | 72  |        |
| 876  | SDSS  | 383         | 92       | 45      | 16    | 32          | 72  |        |
| 1130 | Kinematics | 0         | 0        | 592     | 16    | 32          | 0   |        |
| 1159 | SDSS  | 496         | 67       | 17      | 19    | 32          | 9   |        |
| 1163 | SDSS  | 516         | 73       | 1       | 17    | 32          | 1   |        |
| 1198 | SDSS  | 465         | 88       | 19      | 16    | 32          | 20  |        |
| 1203 | SDSS  | 357         | 121      | 57      | 16    | 32          | 57  |        |
| 1204 | SDSS  | 372         | 94       | 48      | 19    | 32          | 75  |        |
| 53084| 1348  | SDSS        | 510      | 79      | 2     | 17          | 32  | 0      |
| 1368 | SDSS  | 490         | 93       | 3       | 16    | 32          | 6   |        |
| 1375 | SDSS  | 513         | 75       | 0       | 17    | 32          | 3   |        |
| 1379 | SDSS  | 494         | 96       | 1       | 16    | 32          | 1   |        |
| 1380 | SDSS  | 436         | 86       | 43      | 16    | 32          | 27  |        |
| 1440 | SDSS  | 472         | 70       | 20      | 17    | 32          | 29  |        |
| 1453 | SDSS  | 476         | 108      | 1       | 16    | 32          | 7   |        |
| 1619 | SDSS  | 520         | 69       | 0       | 17    | 32          | 2   |        |
| 1758 | SDSS  | 346         | 94       | 57      | 16    | 32          | 95  |        |
| Total |       |             | 3650     | 599     | 799   | 154         | 304 | 254    |

7. LESSONS LEARNED

Probably the hardest section to write in an article such as this is the admission of where we went wrong and the lessons that (we hope!) were learned. Of course, at a low level, many of the day-to-day problems encountered in SDSS operations are very specific to this survey and hence of minimal interest to others. However, many higher-level issues have been recognised since the survey started, and just a few of these with impact on observing strategy and tactics will be mentioned here.

7.1. Doing two things at once is difficult

... Especially when one has to precede the other. The SDSS was designed from the outset with the aim of gathering imaging and spectrographic data on one telescope, with the spectrographic targets being selected from the imaging data. One of the most potentially difficult scheduling problems at the start of a combined survey such as this is the very necessity of obtaining imaging data before targets for spectroscopy could be chosen. This was compounded by the science goals that required observations throughout the year and the stringent observing conditions required for achieving the imaging quality targets.

In fact, as it has turned out, we have very comfortably gained ground, so that at the time of writing, the imaging survey is considerably ahead of the spectral survey, so that we are no longer in any danger of running out of spectral targets to observe. The choice of APO as the site for the SDSS telescopes has been justified not least by achieving the balance of observing conditions required.

7.2. Eventually, you have to (understand how to) select targets

Another serious problem associated with achieving the survey homogeneity objectives is that the spectrographic targeting algorithms were all largely untested on the sky, and consequently underwent considerable evolution from the start of the survey. This has been a particular concern for the quasar targeting, where the loci of galactic stars and quasars cross for quasars at \( z \approx 3 \) in the 4-colour space from which targets were selected. This caused considerable difficulties in achieving the desired redshift selection function, and the targeting algorithm was not frozen until more than 16000 quasars (~ 16 per cent of the expected survey total) had been observed. One penalty of this is that the homogeneous quasar data form a smaller subset of the entire data set than would be desired.
7.3. When you paint a floor, finish near an exit

The aims of the SDSS are to image one quarter of the entire sky, then obtain spectra of $\sim 1.1 \times 10^6$ objects from the same area.\footnote{Being a telescope based on Earth away from the poles, the areas of sky actually accessible for observation varies with season. This leaves us with the natural problem of “painting ourselves into corners”, whereby we have essentially finished large areas of the sky for particular times of year. This problem naturally gets worse as we approach the completion of the survey.} There is therefore a clear need for follow-on programmes to fill the gaps in the schedule. In this the SDSS is unusual, the entire system having been built for the single purpose of conducting the survey, rather than as a general purpose system. Nevertheless, the collaboration seems to have had little problem finding interesting things to do with the “spare” time that has arisen during the course of the survey, although new mechanisms had to be grown to manage the allocation of time and resources to these additional programmes. As the end of the main survey comes into sight, however, the problem will only get worse, and several major proposals for extended follow-on programmes are in progress. The lesson learned here for special-purpose systems on the SDSS model is the need to pay very great attention to the lead times between ideas and funding if operational and staffing continuity is to be achieved. In particular, the risks of losing highly skilled and experienced staff because of a gap in funding are immense, as once they have gone, any follow-on programmes would be essentially starting from scratch in learning how to do things.

7.4. Software will be more complicated than you imagined

The software required to operate the entire SDSS is, as might be expected, large and complex. The code directly associated just with operating the instruments consists of $\sim 10^5$ lines of source code, not counting common subroutines shared with other operational systems. The version number of this code is v3.137.0 which alone tells a long story, and that is but one of the 18 distinct software systems that are used during any night of operations.

Although all the software is now relatively stable (in the sense that it does most of what is required and we know how to work around most of its deficiencies!), it took a long time to reach this state, and as with many one-off software development projects, ended up being far more complex than was at first envisaged. The first author of this article is not alone in holding the opinion that a faster and better job could have been done if the tasks of constructing the software had been managed by professional software engineers instead of professional astronomers, although, clearly, extensive astronomical insight was critical to defining systems requirements.

7.5. You will want to run the machines longer than you imagined

Managing any special-purpose system into a long term asset requires a strategy for evolution and maintenance of the hardware. In the case of the SDSS, there are several hardware systems that represent single-point failure threats to survey operations. In particular, the imager is the single most valuable asset, and a great deal of effort has gone into protecting it. Nevertheless, we have already had several episodes where it appeared for some time that we might lose one or another of the 54 CCDs it incorporates. Spares are limited and compatible replacement hardware would be difficulty to obtain, so observational strategies for softening the effects of failure are necessary. Similarly, any problems with the complex optics and cameras in the spectrographs or any of the associated data acquisition computers would be, if not show stoppers, at the very least the cause of major slow-downs in the survey.

Although it would be nice to declare that everything is and will remain copacetic, everyone is very much aware of all of these potential sources of failure, and plans are in hand to provide short-term and long-term solutions. But we are pleased to report that none of these problems has, as yet, stopped us from continuing to build the largest extragalactic redshift survey so far.

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