Sky Surveys in the Optical and Near-IR: Present Status and Future Prospects

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SDSS image of Coma Cluster core
For decades, the state of the art was the Palomar and ESO sky surveys.
Photographic surveys are not ideal:

- Photographic film has limited dynamic range.
- The quantum efficiency is low, limiting the depth of the survey.
- Wide-field photographs are difficult to accurately calibrate photometrically (for POSS, 0.1-0.2 mags is the current state of the art; Gal et al. 2004).
- The image size is limited by the grain size in the emulsion; at least 2” for the POSS.
- It is not possible to go beyond 1 micron.
- The data are not initially in digital form; digitizing the plates introduces its own artifacts.

This is the way galaxy surveys such as the UGC were compiled...
Wide-field surveys with CCDs (in the optical) or HgCdTe detectors in the near-infrared have close to ideal quantum efficiencies over a broad spectral range.
- Linear response curve over a large dynamic range
- Highly reproducible and calibrateable response; 1% photometry is now feasible.
- The data is already in digital form!
But there are challenges:

- To cover a lot of the sky, you need a *dedicated* wide-field telescope.
- Large format CCDs are expensive; wide-field infrared devices are even more expensive!
- Processing all those data requires a *lot* of software, and a *lot* of processing power.
The Sloan Digital Sky Survey

A consortium of the American Museum of Natural History, Basel, Cambridge U., Case Western Reserve, U. Chicago, Drexel, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins, the Joint Institute for Nuclear Physics, the Kavli Institute (Stanford), the Korean Scientist Group, LAMOST (China), Los Alamos National Lab, Ohio State U., the Max-Planck-Institutes for Astronomy and Astrophysics (Germany), New Mexico State, U. Pittsburgh, U. Portsmouth (UK), Astrophysical Institute Potsdam (Germany), Princeton U., the US Naval Observatory and U. Washington.

The goals:

To use a dedicated telescope to survey the Northern Sky, in five photometric bands using modern CCD technology over 10,000 square degrees.

A spectroscopic redshift survey of a million galaxies and one hundred thousand quasars to study their properties and distribution in space. An emphasis on highest quality photometric and astrometric calibration.
SDSS sky coverage, summer 2005

8000 deg$^2$, 2×10$^8$ objects

5740 deg$^2$, over one million spectra
A dedicated 2.5m wide-field telescope

Telescope has a 3 degree field of view, focal ratio of five. Located at Apache Point Observatory in Southeast New Mexico.

It observes without a dome; it is protected from wind buffetting and stray light by a comoving light baffle structure.

There is an auxiliary 20-inch telescope for photometric calibration.
SDSS imaging camera, built by Jim Gunn et al. Shown here mounted on the telescope.

Interior view of the camera, showing the filters on the corrector plate.
SDSS camera schematic

A drift-scan camera. 54.1 seconds in each filter, in order r, i, u, z, g

54 CCDs on focal plane; 145 Mpix.

Data rate of 5 Mbytes/sec.

Sky is covered at rate of 20 square degrees per hour.
SDSS filter curves, both with and without the atmosphere.

Covers the full atmospheric window reachable with CCDs.
SDSS spectrographic cartridge mounted on telescope and mated to spectrograph.

We take spectra of 640 objects at a time, with typical exposure times of one hour.

Resolution
$\Delta \lambda / \lambda = 2000$

Coverage
3800-9200 Å
Spectra of 640 objects at a time: magnitude-limited sample of galaxies, a magnitude- and color-selected sample of quasars, plus all FIRST sources with unresolved optical counterpart $i < 19$. Fibers feed a pair of double spectrographs

SDSS spectrographs are hot!

![Diagram of SDSS Spectra]
Spectrographs are fed by 3" fibers hand-plugged into machined plugplates.
An example of synergy between SDSS and FIRST: Dependence on quasar radio-loud fraction on redshift and luminosity

The fraction of SDSS quasars that are radio-loud (based on K-corrected radio/optical flux ratio) as function of redshift, luminosity. 

Jiang et al. 2006, submitted
White et al. (2006) find no redshift dependence in the median radio luminosity as function of optical luminosity.
The position of the ridgeline of the stellar locus is a powerful test of the uniformity of photometric calibration.
The position of the stellar locus has rms variations of ~1%.

Variation in position of stellar locus across survey area. Plotted scale ranges ± 2%

Photometric calibration is done by forcing agreement in overlaps between runs (similar in spirit to CMB experiments like WMAP)

Padmanabhan, Finkbeiner, Schlegel et al. 2006
Spectrophotometry is good to ~5% in broadband, with even smaller residuals on smaller wavelength scales.

Imaging versus integrated spectra

WD spectra - best-fit models

Courtesy Christie Tremonti
In the near-IR: the Two Micron All-Sky Survey

Matched 1.3m telescopes at Mt. Hopkins and CTIO
• Simultaneous imaging in JHK, integration of 10 seconds.
• True all-sky (99.997% coverage!) survey, with dynamic range of over 10 magnitudes, to a depth of K~14.3 (10σ). This is a bit deeper than SDSS galaxy spectroscopy.

Uniform photometric calibration to 1% over the entire sky.

Mean offset of nightly standard star solution from global solution, Nikolaev et al. 2000
Astrometry good to ~80 mas rms per coordinate (very impressive for 2” pixels!)

Comparison of 2MASS astrometry to that of UCAC.
2MASS Covers the Sky

The Two Micron All Sky Survey
Infrared Processing and Analysis Center/Caltech & Univ. of Massachusetts
The 2MASS Galaxy Distribution in Supergalactic Coordinates

Two Micron All Sky Survey Image Mosaic Infrared Processing and Analysis Center/Caltech & University of Massachusetts

The Infrared Universe: Light from 1.4 million galaxies reveals the structure of the local universe
What we have learned from these surveys

• We don’t know how we got by before these surveys existed. These are absolutely fundamental data. Lots of important papers are redoing classic analyses (e.g., the luminosity distribution of galaxies, the color distribution of stars, etc.)

• 1% photometry really is important. Systematic errors substantially larger than this will affect:
  • Measurements of large-scale structure, which depend on uniformity of sample selection;
  • separation of giants from dwarfs in broad-band colors
  • Photometric redshifts of galaxies
The astrometric reference frames between radio, optical, and near-IR are now tied together better than 100 mas. But proper motions in the halo are of order few mas/year, so we can really use better astrometry.

SDSS and 2MASS have very little repeat observations. The time-variable sky (AGN, variable stars, gamma-ray burst afterglows, supernovae, flare stars, novae, white dwarf pulsations, transiting planets, KBOs, high proper motion stars, etc., etc.) are becoming increasingly important.

The synergy between surveys at different wavebands (including the radio, of course!) is increasingly important, to understand the full SEDs of objects.
Quality, quality, quality

- Use the physics problem at hand to design the telescope, instruments, and survey strategy.
- Given those things, we must get the highest-quality data that the laws of physics and astronomy allow.
- This is the only way you can fully understand the systematics of our data, and it will allow analyses more sophisticated than we can think of now, tackling problems we don’t yet have the imagination to consider.
Scientific drivers (especially in the high-redshift universe) suggest that it would be very valuable to go many magnitudes fainter than SDSS, 2MASS. For example, SDSS doesn’t go nearly deep enough to see high-redshift radio galaxies.

High-quality spectra (not just “good enough for a redshift”) have been tremendously valuable. Spectra give enormously more information than does broad-band photometry.

There is no substitute for high-quality data, processed with high-quality software. You cannot hope to go deep, with 1% photometry and tens of milli-arcsecond astrometry, and be sloppy! You can’t be sloppy, and hope to ferret out subtle systematics in the data.

Big surveys require large groups of astronomers, and the political challenges are at least as large as the technical challenges. Managing big projects is a real challenge.
The big questions the next generation of surveys will address:

- The nature of dark energy, probed by weak lensing, baryon oscillations, supernovae, etc.
- Structure in the Milky Way halo: evidence of cannibalism.
- Searches for near-Earth asteroids, Kuiper Belt Objects, etc.
- Understanding the transient Universe.
Baryon Oscillations as a standard ruler

The oscillations seen in the CMB power spectrum are at a fixed comoving scale: a standard ruler to be studied as a function of redshift, thus constraining the geometry of the universe.

**WMAP:** Spergel et al. 2003, 2006

**SDSS:** Eisenstein et al. 2005
Next-generation imaging surveys underway:

<table>
<thead>
<tr>
<th>Survey</th>
<th>Primary mirror (meters)</th>
<th>Filters</th>
<th>Depth (5 σ)</th>
<th>Sky coverage (deg²)</th>
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<tr>
<td>CFHT Legacy</td>
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<td>UBRIriz</td>
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## Future imaging surveys

(list is not complete!)

<table>
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<tr>
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<th>Filters</th>
<th>Depth (5 $\sigma$)</th>
<th>Sky coverage (deg$^2$)</th>
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Plans for the next generation of spectroscopic surveys are much less developed. The science drivers are clear: you learn much more astrophysics with a spectrum, and photometric redshifts are not a panacea.

- RAVE survey will measure radial velocities (narrow spectral coverage) for up to $10^6$ stars to $I \sim 12$.

- Future extragalactic surveys, to study baryon oscillations, galaxy properties, etc., are being discussed for Subaru (WMOS, WFMOS), HET (VIRUS), and San Pedro Martir.
Conclusions

- Optical and near-infrared astronomers have discovered the value of well-calibrated and well-characterized surveys.

- Existing surveys (SDSS and 2MASS) have only whetted our appetite. The next generation of surveys will go substantially deeper and will have a major time-variable component.

- Most of the planned surveys are focussing on imaging; major spectroscopic surveys are being thought about, but there is less competition for them thus far (see Arjun Dey’s talk).