SDSS-II Supernova Survey

Josh Frieman
SDSS Science Symposium
August 18, 2008
SNe from SDSS Southern stripe: an old idea

• Newberg, Munn, and Richmond ~1993
• Hogan and others: Southern Working group 1994

SUPERNOVAE

Bohdan Paczynski, June 26, 1994

I am in favour of establishing facts first. I think it should be possible to use the first southern strip season to determine the following:

1. The supernovae rate in galaxies and outside of galaxies.
2. How good standard candles SN Ia really are?

To answer these question it is sufficient and necessary to recognize all SN Ia brighter than 20 mag at maximum and to obtain their spectra. Note, that the so called “peak luminosity” is best determined with the whole light curve, the most critical region being the transition from the broad “bulge-like” maximum (which lasts about one month) to the quasi-exponential tail; the transition is about 3 mag below the peak (Press et al 1994).

The average peak magnitude of SN Ia is approximately given as

\[ m_{B,max} \approx 19.1 + 5 \log(z/0.1), \]

(Bohr and Tammann 1992, and references therein). Supernovae of Type Ia form a one parameter family, with a very small scatter in the peak magnitude when the dependence on that phenomenological parameter is taken into account (Phillips 1993). According to Press et al. (1994) the residual scatter is no more than
From SDSS to STSS: Synoptic Time-Domain Survey Science
Craig J. Hogan on behalf of the Time Domain Team

ABSTRACT

We describe two forefront time-domain survey projects where the SDSS 2.5m telescope and camera system can make critical contributions, namely 1) the detection and characterization of Solar System objects and 2) obtaining type Ia supernova light curves in the redshift range \(0.05 < z < 0.35\). For the Solar System objects, we demand not only detection but characterization of orbits and compositions, and estimate the overall detection efficiency using detailed simulations. We show that the 2.5m is uniquely poised in the next five years to make an outstanding contribution to the NASA goal of detecting 90\% of the potentially hazardous asteroids with diameters 1 km and larger. For the supernovae, we demand densely-sampled multiband light curves with much better photometric calibration and spectral coverage than are currently available, and estimate the sample quality and size using Monte Carlo simulations; we find that a realistic program would produce hundreds of light curves of unprecedented quality. The supernovae would fill an important gap in redshift space, providing unique new foundational knowledge of both intrinsic supernova properties and an important part of the Hubble diagram, including the best direct measurement ever made of the cosmic deceleration parameter \(q_0\) and important constraints on the nature of dark energy. Both of these project simulations are reliably calibrated using actual SDSS time-domain data. Both proposed projects will make unique contributions, well beyond the capabilities of existing projects within a five year time frame, that are well aligned with key strategic priorities of the science community (as described in three recent NAS reports), major funding agencies (NSF, DOE, and NASA), and potential new partners.

The Sloan Digital Sky Survey and Supernovae Ia

By Joshua A. Frieman (for the SDSS Collaboration)

The Sloan Digital Sky Survey (SDSS) will produce a 3D map of the universe of galaxies over a volume \(4 \times 10^5 h^{-3} \text{ Mpc}^3\). Covering \(\pi / 2\) centered on the north galactic cap, the SDSS will comprise a photometric (CCD) imaging survey of \(10^6\) objects in 5 wavebands, a magnitude-limited spectroscopic (redshift) survey of \(10^5\) galaxies and \(10^5\) quasars, and a nearly volume-limited redshift survey of \(10^5\) bright red galaxies. The less-well-known southern SDSS will include repeated imaging of a \(\approx 225\) sq. deg. region (to limiting magnitude \(r' \approx 23\) per exposure) and should be useful for study of variable objects, including supernovae. This talk provides a brief overview of the SDSS and its possible contributions to the study of Type Ia supernovae.

The Sloan Digital Sky Survey (SDSS) (York, et al. 1997) is a wide-area photometric and spectroscopic survey of the sky being carried out with a dedicated 2.5m telescope at Apache Point Observatory in southern New Mexico. While designed primarily to study galaxies, quasars, and their clustering properties in detail, the SDSS should prove a valuable tool for investigating a variety of variable phenomena in the sky, including supernovae. This short review provides an introduction to and status report on the SDSS, followed by some thoughts on detecting Type Ia SNe in the course of the survey.
Cosmic Acceleration Discovery from High-redshift SNe Ia

SNe at $z \sim 0.5$ are $\sim 0.25$ mag fainter than in an open Universe with same value of $m$. $\Omega_m = 0.7$ and $\Omega_\Lambda = 0.0$. $\Omega_m = 1.0$, $\Omega_\Lambda = 0.0$. $m = 1$. 
SN Ia Hubble Diagram

- goal of the SDSS SN survey: fill in SN Ia Hubble diagram at redshifts $0.1 \leq z \leq 0.3$
  - connect low-z with high-z
  - test the concordance cosmology
- challenges
  - peak magnitude $m = 20-22$
  - must search hundreds of square degrees of sky

→ SDSS 2.5m telescope + imager

http://sdssdp47.fnal.gov/sdsssn/sdsssn.html

Jha
SDSS II Supernova Survey Goals

• Obtain few hundred high-quality SNe Ia light curves in the `redshift desert’ $z\sim 0.05-0.35$ for continuous Hubble diagram
• Detailed spectroscopic follow-up, including some with multiple epochs, to study evolution and diversity of SN features
• Probe Dark Energy in $z$ regime complementary to other surveys
• Well-observed sample to anchor Hubble diagram & train light-curve fitters
• Rolling search: determine SN/SF rates/properties vs. $z$, environment
• Rest-frame $u$-band templates for $z > 1$ surveys
• Large survey volume: rare & peculiar SNe, probe outliers of population
• Enable time-domain science both in real time* & after the fact**
  *candidates immediately on the web+IAU circulars+VOEventNet
  **SN images & object catalogs all available publicly
## Spectroscopic follow-up telescopes

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<td>U Chicago</td>
<td>B. Dilday, R. Kessler, M. Subbarao (Adler Planetarium)</td>
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<td>U Washington</td>
<td>A. Becker, C. Hogan, J. VanderPlas</td>
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<td>Wayne State</td>
<td>D. Cinabro, Matt Taylor</td>
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<td>SNU</td>
<td>C. Choi, M. Im</td>
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<td><strong>HET team</strong></td>
<td>Goettingen (W. Kollatschny), Munich (R. Bender, U. Hopp), U Texas (C. Wheeler, P. Hoeflich)</td>
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<td><strong>Subaru team</strong></td>
<td>Y. Ihara</td>
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<td><strong>KPNO team</strong></td>
<td>M. Florack, A. Hirschauer, D. O’Connor</td>
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<tr>
<td><strong>Keck team</strong></td>
<td>R. Foley, A. Filippenko</td>
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Use the SDSS 2.5m telescope
- September 1 - November 30 of 2005-2007
- Scan 300 square degrees every 2 days
- Obtain densely sampled multi-color light curves

### Searching For Supernovae

<table>
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<th>Year</th>
<th>Scanned</th>
<th>Candidates</th>
<th>Confirmed Ia</th>
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<tr>
<td>2005</td>
<td>-</td>
<td>-</td>
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<tr>
<td>2006</td>
<td>14,441</td>
<td>3,694</td>
<td>193</td>
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<tr>
<td>2007</td>
<td>175</td>
<td>-</td>
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- Positional match to remove movers
- Insert fake SNe to monitor efficiency
Rolling survey leads to well-sampled*, well-constrained light curves

*r = 22.5 for typical SN Ia

*9 epochs of imaging per SN (median)
SDSS SN Photometry: Holtzman et al. (2008) in press
Spectroscopic Target Selection

2 Epochs

SN Ia Fit

SN Ibc Fit

SN II Fit

Sako et al. 2008
Spectroscopic Target Selection

2 Epochs
SN Ia Fit
SN Ibc Fit
SN II Fit

31 Epochs
SN Ia Fit
SN Ibc Fit
SN II Fit

Fit with template library
Classification >90% accurate after 2-3 epochs
Redshifts 5-10% accurate
Sako et al. 2008
SN and Host Spectroscopy

MDM 2.4m
NOT 2.6m
APO 3.5m
NTT 3.6m
KPNO 4m
WHT 4.2m
Subaru 8.2m
HET 9.2m
Keck 10m
Magellan 6m
TNG 3.5m
SALT 10m

2005+2006

Number of Spectroscopic epochs vs Redshift

2005gj
2006fo
2005hk
2006fz
SN Ia Spectra

1325 spectra taken over 3 seasons
Spectroscopic Deconstruction

484 confirmed SNe Ia with IAU designations
~500 spectroscopically confirmed SNe Ia

~50 spectroscopically probable SNe Ia

~20 SNe Ib/c

~60 SNe II

~200 photometric SNe Ia with host galaxy redshifts and counting
SDSS-II SN Science

"SN Ia rate at low redshift (Dilday et al 2008)
"SN Ia rate vs. redshift; SN Ia rate in clusters (Dilday)
"SN Ia rate and properties vs. host-galaxy properties (Smith)
"UV evolution of SNe Ia (Foley)
"Hubble Diagram and Cosmology from 2005 season (Kessler, Becker, VanderPlas, Cinabro, & )
"BAO vs. SN distance scales (Lampeitl, Seo)
"Testing Exotic cosmologies (Sollerman, Davis)
"SN spectroscopic studies (Zheng; Konishi; Ostman, Nordin, Stanishev)
"SN Ia Rise and Fall time distributions (Hayden, Garnavich)
"Late-time properties of 2005hk (Jha)
"Light-curve studies with multi-band stretch method (Takanashi)
"Luminosity functions of SNe Ia and their hosts (Yasuda)
"Core-collapse SN Rate (Taylor)
"Cross-calibration of SDSS and CSP (Mosher)
"NIR SN observations (Goobar)
"Study of SN colors (Paech)
"Follow-up studies of SN host galaxies (Sako, Garnavich, Nichol, Marriner & )
"Type II, IIn, IIp studies (Tokita; Ihara; D Andrea)
"SN Cosmology with photo-z's (Bassett)
Low-redshift ($z < 0.12$) SN Ia Rate (2005 data)

29 confirmed SNe Ia before cuts

• 1 outside range of calibration star catalog
• 3 are peculiar (including 2005hk and 2005gj)
• 4 SNe have no observations at $t < -2$ days
• 5 SNe have no observations at $t > 10$ days

16 confirmed SNe Ia after cuts

Dilday
Low-redshift ($z<0.12^*$) SN Ia Rate (2005)

$\text{Rate} = (2.9^{+0.2}_{-0.04} \pm 0.7) \times 10^{-5} \text{ (Mpc}/h_{70})^{-3} \text{ year}^{-1}$

Volumetric rate at mean $z = 0.09$

Compilation of rate measurements

Dilday, et al

*spectroscopically complete
SN Ia Rate vs. Redshift (2005+6)

SN Selection

\[ Z < 0.20 \]
132 SNe
68% spec. confirmed
88% with redshifts

\[ Z < 0.25 \]
248 SNe
54% spec. confirmed
74% with redshifts

562 total SNe candidates with \[ z < \sim 0.45 \]
Rate vs redshift slope for $0.1 < z < 0.2$:

$$dr/dz = (1.37 \pm 0.69) \times 10^{-4} \text{ SNe yr}^{-1} \text{ Mpc}^{-3} h_{70}^{-3}$$
SN Cluster Rate vs. Redshift

Consistent with a constant rate as a function of redshift

Preliminary
MLCS2k2 model templates

Δ = -0.3: bright, broad
Δ = +1.2: faint, narrow

Jha et al, 2007
SN Ia vs. Host Galaxy Properties

Luminosity

Smith et al
SN Ia vs. Host Galaxy Properties

Reddening/color

Smith et al
SN Ia vs. Host Galaxy Properties

Log SN Rate (per unit mass per year)

Passive          Star-forming          Burst

SDSS Preliminary
SNLS
Mannucci et al.

Log Specific SFR (M_☉ yr⁻¹ per unit stellar mass)
Fitting SN light curves: MLCS2k2

" Multicolor Light Curve Shape (Riess et al '98; Jha et al '07)

" Model SN light curves as a single parameter family, trained on low-\(z\) UBVRI data from the literature (Hamuy et al '96, Riess et al '98, Jha et al '07)

" Assumes SN color variations are due to dust extinction, subject to prior

" Rewritten to fit in flux, not magnitude

\[
m^\ast_X(t - t_0) = M^0_X + \mu_0 + \zeta_X (\alpha_X + \beta_X / R_V) A^0_V + \bar{P}_X \Delta + \bar{Q}_X \Delta^2,
\]

Time of maximum  distance modulus  dust law  extinction  stretch/decline rate

Time-dependent model “vectors”

fit parameters

\(P(A_v)\)
SALT II Light-curve Fits

"Fit each light curve using rest-frame spectral surfaces*:

\[
\frac{dF_{\text{rest}}}{d\lambda}(t, \lambda) = x_0 \times [M_0(t, \lambda) + x_1 \times M_1(t, \lambda)] \times \exp[c \times CL(\lambda)]
\]

"Transform to observer frame:

\[
F_{\text{obs}}^f(t) = \frac{1}{1+z} \int d\lambda' \left[ \frac{dF_{\text{rest}}}{d\lambda'}(t, \lambda') \times T^f(\lambda' \cdot (1+z)) \right]
\]

"Light curves fit individually, but distances only estimated globally:

\[
\mu_i = m_{B_i}^* - M + \alpha \cdot x_{1,i} - \beta \cdot c_i
\]

Global fit parameters, determined along with cosmological parameters

"*Not trained just on low-redshift data; distances are cosmology-dependent, flat priors on model parameters
Light Curve Fitting with MLCS2k2 and SALT-II
Monte Carlo Simulations match data distributions

Use actual observing conditions (local sky, zero-points, PSF, etc)
Model Survey Efficiency

SDSS-II Efficiency vs. Extinction

- z=0.1  $\Delta = -0.3$
- z=0.3  $\Delta = -0.3$

- subtraction pipeline
- search = pipeline + spec
- search + cuts

- z=0.1  $\Delta = 0.5$
- z=0.3  $\Delta = 0.5$
Model Spectroscopic & Photometric Efficiency
Extract $R_V$ distribution from SDSS SN data

- $R_V = \frac{A_V}{E(B - V)} < 2$

- MLCS previously used Milky Way avg $R_V = 3.1$

- Lower $R_V$ more consistent with SALT color law

D. Cinabro
MLCS Extinction vs. SALT Color

\[ A_\lambda - A_V \text{ [mag]} \]

- \( R_V = 1.9 \)
- SALT2
- \( R_V = 3.1 \)

\[ E(B-V) = 0.10 \]

Jha
Extract $A_v$ Distribution from SDSS

![Graph showing distribution of $A_v$ and $\Delta$ with data from SDSS-II, simulated fits, and generated simulations.](image)
Preliminary Cosmology Results

Kessler, Becker, et al. 2008
Comparative Hubble Diagram

MLCS V30 vs. SALT 0706 for sample d

$\langle \delta \mu \rangle = 0.07513011992$

$\sigma(\delta \mu) = 0.2407609224$
Issues with rest-frame U band

- Data vs. SALT Model Residuals
- ESSENCE, SDSS similar to SNLS
- Similar Low-z vs. High-z discrepancy seen in MLCS
- MLCS trained only on Low-z, SALT model dominated by High-z
- Similar differences seen in rest-frame UV spectra (Foley et al)
Rest-frame U band differences

MLCS V31-lam4300deweight vs. SALT (no cut) for sample d

\[ \langle \delta \mu \rangle = 0.1417315304 \]
\[ \sigma(\delta \mu) = 0.1830913478 \]
**SN vs BAO Distances**

SNe: \[ D_L = (1 + z)D_M = (1 + z)f(z) \]

BAO: \[ D_V = \left( D_M^2 \frac{z c}{H(z)} \right)^{1/3} = (zf^2 f^{-1/3}) \]

Lampeitl, Seo, et al
Future: Improved SN Ia Distances