# Supernova Studies With LSST + Other Observatories

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## ABSTRACT

An LSST supernova search and follow-up program is explored in terms of the photometric, spectroscopic, and NIR requirements demanded by the SNAP experiment. The multiplexing advantage that the LSST has for $B$-band light curve building is maintained up to $z \sim 0.8$ while the color-excess measurement requirement restricts LSST depths to $z \sim 0.7$. The LSST provides no spectroscopic nor NIR capabilities so we must consider the value added when including the resources of other observatories. The addition of near-infrared imaging with the Subaru allows deeper follow-up but limits the number of higher-redshift supernovae that can be followed in its smaller field of view. Subaru spectroscopy with OH suppression or AO can fulfill spectroscopic requirements to $z \leq 1.1$ and $z \leq 1.8$ respectively, although the latter does not provide the requisite NIR spectrophotometry. The NIR requirement can only be obtained by a very large-aperture telescope (CELT) or a space telescope (NGST).

## 1. Introduction

The design of SNAP is based on reducing systematic error from all sources, including magnitude variations due to the disparities in supernova progenitor systems that are not corrected by stretch and color corrections. Theoretical models indicate that spectra and light-curve rise times and plateau levels can vary depending on the details of the progenitor system. Although clear correlations between them and the SN peak magnitude have not yet been observed, SNAP is being designed to measure these parameters at the levels where they are theoretically expected to be important. Accurate measurements of the faint supernova well before and after it reaches maximum light are necessary to accomplish this.

An additional systematic error that needs to be addressed is from possible "grey" dust along the line-of-sight which dims the supernova. Dust grain models have successfully been constructed to have the desired effect but due to their finite size the dust does produce reddening in the NIR. SNAP is able to identify the existence of this possible grey dust by observing out to 1.7$\mu$m, either spectroscopically or photometrically.

K-correction error requirements enter obliquely into the supernova observing strategy. These errors are reduced when observer filters closely match standard filters in the supernova frame, we thus demand observation with a fixed set of filters optimized at uniformly distributed redshift bins, e.g. $B_0$, $B_{0.1}$, $B_{0.2}$, …, $V_0$, $V_{0.1}$, $V_{0.2}$, … where we denote observer filters that match $B$ and $V$ in the redshift $z$ frame as $B_z$ and $V_z$. The time required to observe the supernovae $z \ll z_{max}$ is relatively small but is considered in our analysis.

Obtaining high-precision measurements of high-redshift supernovae from the ground is intrinsically limited by "flat-field" error: systematic variation of the system throughput pixel-to-pixel that is not accounted for by the flatfield. Although these errors tend to be small, $10^{-4}-10^{-3}$ (McLean 1997), large sky backgrounds can magnify the errors into fluctuations comparable in flux to faint supernovae. SNAP quality observations from the ground are thus inherently redshift limited.

We examine how a dedicated LSST supernova search and light-curve survey performs with these observational requirements. We also consider the value added incorporating other observatories into the program with NIR photometry and spectroscopy. We use a sophisticated exposure-time calculator (ETC) which incorporates established system throughputs, optics, quantum efficiencies of LBNL CCD's and HgCdTe detectors, sky transmission and emission, and seeing distributions for the VLT (for LSST calculations) and Subaru. As a check of its reliability, the ETC does reproduce observed signal-to-noises from previous ground searches.

## 2. Photometry

SNAP has photometric requirements for the supernova rest-frame $B$ and $V$ magnitudes. The first is an accurate measurement of dust extinction $\delta A_{B_z} < 0.1$ mag or $\delta B_z \sim \delta V_z \sim 0.02$ mag. The application of an extinction correction is necessary and must be considered for all cosmological uses of SNe Ia, including SN searches by SNAP or the LSST. An even more stringent $B_z$ requirement is to measure $S/N = 10$ points 2.5 magnitudes below peak brightness. Observations to this depth taken every four rest-frame days ensure elimination of Malmquist bias and accurate measurements of the date of explosion and the plateau level of the light curve. The last two statistics have been identified as possibly parameterizing the SN Ia family independently of stretch.

We have calculated the limiting redshifts at quarter moon for 9 hour exposures in both the $B_z$ and $V_z$ bands for several telescopes for seeing conditions that occur 68% and 90% of the time. From Monte Carlo studies we find the 68%-ile seeing at these conditions are a fair representation of realistic light-curve quality, including varying lunation, seeing, and weather effects. The results are listed in Table 1 and are summarized below:

- SNAP — These numbers correspond to baseline SNAP observing times.
- LSST — The LSST will have no NIR camera, which sets a $z < 0.7$ limit for $V_z$ observations. Multiplexed $B$-band light curve building is limited to $z < 0.77$.

NIR photometry can expand the redshift reach of the LSST search, but detectors sensitive to only longer than 1 $\mu$m can only observe $V_z$ at $z > 0.8$ and $B_z$ at $z > 1.3$.

- Subaru/IRCS — Ground-based NIR observing is limited by OH emission but can obtain the $V_z$ measurement just at $z = 0.79$. SNAP-quality $B_z$ measurements are not possible for the allowed region $z > 1.3$.
- Subaru/IRCS/OHS — OH suppression increases further the redshift reach for $V_z$ measurements to $z = 1.23$ and allows redshifted $B_z$ observations at $z \sim 1.3$.
- WFC3 — NIR imaging in space makes SNAP-quality photometry possible, although the SNAP $B$-band criterion will require very long exposures.

The redshift reach for the photometric follow-up requirements (not discovery) are summarized as follows.

| Filter | LSST | IRCS | OHS | WFC3 |
|---|---|---|---|---|
| $B_z$ | $< 0.77$ | $\cdots$ | $\sim 1.3$ | $< 1.25$ |
| $V_z$ | $< 0.7$ | $\sim 0.8$ | $0.8 - 1.23$ | $< 1.72$ |

The NGST could easily provide photometry of high-redshift supernovae as $B$ and $V_z$ observations of $z = 1.7$ supernovae would require 4 and 8.6 minutes respectively. The average major slew and settling times for the NGST are 60 and 15 minutes respectively; NGST time would not be efficiently used for observing such "bright" objects!

## 3. Spectroscopy

In this section, we examine the value added to an LSST search by additional spectroscopic observations. Theoretical models predict observable variations in spectral features such as line velocities, widths, and depths as a function of the progenitor system. SNAP, as a space-based mission, can measure these features free from the sky continuum, OH-emission, and water absorption that plague observations through the atmosphere. Qualitatively, the SNAP spectroscopy requires the identification of the SiII feature at 6150Å, $S/N = 5$ for a 30Å restframe bin, and $S/N = 10$ for a 30 Å bin between 3500–4800Å. Table 2 summarizes the observational requirements and the redshift reach of different instruments.

We consider the 8-m Subaru telescope and the proposed 30-m CELT supplemented with OH-suppression and/or adaptive optics. Most of the NIR sky flux comes from narrow OH lines. With very high-resolution spectroscopy, these lines can be isolated and removed. To minimize the background, we consider high resolution $R \sim 10000$

Table 1
Telescope Photometry Redshift Depth at Quarter Moon

| Telescope | $V_z$ Requirement[a] Seeing 68%ile $z_{max}$ | $V_z$ Seeing 68%ile $t$ (hours) | $V_z$ Seeing 90%ile $z_{max}$ | $V_z$ Seeing 90%ile $t$ (hr) | $B_z$ Requirement[b] Seeing 68%ile $z_{max}$ | $B_z$ Seeing 68%ile $t$ (hr) | $B_z$ Seeing 90%ile $z_{max}$ | $B_z$ Seeing 90%ile $t$ (hr) | NIR Req.[c] Seeing 68%ile $z_{max}$ | NIR Seeing 68%ile $t$ (hr) | FOV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SNAP | 1.7 | 3.86 | N/A[d] | | 1.7 | 4.30 | N/A[d] | | 1.7 | 2.47 | 1□° |
| LSST | 0.68 | 9 | 0.60 | 9 | 0.77 | 9 | 0.68 | 9 | N/A[e] | | 7□° |
| Subaru(IRCS) | 0.79 | 9 | 0.69 | 9 | N/A[f] | | | | N/A[e] | | 60" X 60" |
| IRCS+OHS | 1.23 | 9 | 1.11 | 9 | 1.27 | 9 | 1.20 | 9 | 0.51 | 9 | 60" X 60" |
| WFC3 | 1.72 | 9 | N/A[d] | | 1.25 | 9 | N/A[d] | | ... [g] | | 120" X 120" |

[a]To get $V_z$ magnitude to 0.02 mag, or $S/N = 50$ at maximum.

[b]To get $B_z$ 2.5 magnitudes fainter than peak to $S/N = 10$.

[c]To measure $S/N = 30$ in a 1500Å bins in the 1–1.7$\mu$m region.

[d]There is no seeing variation in space-borne telescopes.

[e]These telescopes are incapable of obtaining the requisite NIR observations.

[f]This instrument has no optical sensitivity. Supernovae at redshifts where $B_z$ is in the NIR are too faint for Subaru to observe them.

[g]The WFC3 ETC is momentarily not working. This should be updated

so that the diffraction wings of the very bright lines do not contribute significantly to the continuum. The continuum still contributes one-fiftieth of the total flux and is thus non-negligible (Maihara et al. 1993). It is also highly variable from night-to-night and even within a single night by over a factor of ten. Adaptive optics reduce the background flux on which the supernova lies thus increasing its signal-to-noise. Unfortunately AO is inherently non-photometric. The system throughput, sky to detected photon, is taken to be 10% for OH-suppression and the AO has a Strehl ratio of 0.3.

The spectroscopy of nearby $z < 0.5$ supernovae found by the LSST searches could be done with a wide-field multi-object optical spectrograph, such as the 2dF at the AAO. Such a telescope would be run in survey-mode, much like the LSST, with simultaneous observation of multiple supernovae. A supernova at $z = 0.5$ at maximum light observed with a 3 hour exposure with the 270R grating and with 1" seeing and grey conditions would give a $S/N = 3.78$ for each 4.8Å pixel at 7000Å satisfying our observing requirements. (This is in fact quite optimistic for the AAO, where arcsecond seeing is achieved only 10% of the time (Tinney 1996) but it does demonstrate that at a site with reasonable seeing, existing instrumentation at a 4-m could do well.) At higher redshifts the SiII feature enters the NIR and is inaccessible to an optical detector.

From our experience at Keck, we find that the SiII identification requirement is impossible to obtain for $z > 0.5$ without AO and/or OH-suppression. The fluxes (surface brightnesses) at the restframe 4400Å region for a $z = 1$ and $z = 1.7$ supernova, in $\gamma\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{Å}^{-1}$ ($\mathrm{arcsec}^{-2}$) units are as follows.

| Source | Flux $z = 1$ | Flux $z = 1.7$ |
|---|---|---|
| SN | $1.5 \times 10^{-7}$ | $3.9 \times 10^{-8}$ |
| Continuum | $1.3 - 38 \times 10^{-6}$ | $1.9 - 57 \times 10^{-6}$ |
| SB=22 Host | $1.5 \times 10^{-7}$ | $4.7 \times 10^{-8}$ |

In the calculations below, we take the *lowest* level of sky continuum. The flux is taken to be slightly lower than given in Maihara et al. (1993) where diffraction wings of the strong OH lines appears to have caused an overestimate of the background level.

Table 2

Spectroscopic Redshift Depth: Minimal Continuum and 0.6” Seeing

| Observing Requirement | AAO | Subaru AO | Subaru OHS | CELT OHS[a] |
|---|---|---|---|---|
| SN-frame 3500-4800Å[b] | $z \leq 0.5$ | $z \leq 2.1$ | $z \leq 1.2$ | $z \leq 2.1$ |
| SN-frame SiII[c] | $z \leq 0.5$ | $z \leq 1.8$[d] | $z \leq 1.1$ | $z \leq 1.9$[d] |
| Observer-frame NIR [e] | X | X | $z \leq 0.4$ | $z \leq 2.2$ |

[a]Assumes thermal control of the 30-m telescope so sky-emission is the dominant background.

[b]To measure $S/N = 10$ in 30Å bins in the supernova-frame 3500-4800 Å region.

[c]To measure $S/N = 5$ in 30Å bins in the supernova-frame 6150 Å region.

[d]With a hole at $z = 1.4$ due to water absorption.

[e]To measure $S/N = 30$ in 1500Å bins in the 1–1.7$\mu$m region.

With AO, the SiII feature can be identified out to $z = 1.8$, except where the line happens to fall in a region of water absorption, $z \sim 1.4$. The $3500 - 4800$Å signal-to-noise can be obtained at $z \sim 2.1$. CELT without AO offers practically the same depth as Subaru with AO. For Subaru without AO and 0.6” seeing the SiII feature is accessible at $z = 1.1$ while the $3500-4800$Å region could be fulfilled out to $z \sim 1.8$.

The strong dependence of the exposure times on seeing is demonstrated for the $3500-4800$Å region where a $z = 1.7$ supernova would take 17, 66, and 183 hours for 0.3, 0.6, and 1 arcsecond seeings respectively again assuming minimum sky continuum background (there is some water absorption in this region). Similarly, a $z = 1.2$ supernova observation would require 2.25, 8.7, and 24 hours.

A large (but not monopolistic) amount of time at the NGST could observe the couple hundred highest redshift supernovae with SNAP-quality spectroscopy of a $z = 1.7(1.2)$ supernova in only 4.86(1.63) hours each.

## 4. NIR

The measurement of grey dust requires either photometric or spectroscopic NIR observations out to $\lambda = 1.7\mu$m, where the dust is no longer “grey”. SNAP calls for 10% of its supernovae to have $S/N = 30$ in 1500Å bins in the 1–1.7$\mu$m observer-frame region. The photometric and spectroscopic capabilities of measuring this are given in Tables 1 and 2. As colors are the primary measurement, precise relative photometry over broad wavelength ranges are necessary.

It is very difficult for ground-based instruments to obtain this quality data. Even an 8-meter telescope can go out to only $z \sim 0.5$. (Note that Subaru photometry has larger reach since its OH-suppression system is assumed to have better throughput than its spectroscopic counterpart.) A huge light-bucket, such as CELT, improves the situation and indeed has a redshift reach beyond those targeted by SNAP. This assumes that the technical challenges (thermal, tracking) imposed by an overwhelmingly large telescope can be overcome.

## 5. Possible Scenarios

Based on these observing requirements and the redshift ranges of different instruments, we can construct a supernova observing strategy that maximizes the survey depth. The redshift depths, fields of view, and numbers of supernovae available for study are given in Table 3 and explained in the following.

1. LSST + CELT — By itself, the LSST will be able to go out to $z \sim 0.7$, limited by the $V_z$-band requirement. The $V_z$-band measurement has to be made within around one

observer-week of supernova maximum, otherwise the fainter supernova would be harder to observe. The $B_z$-band measurements at this redshift each require 1.25 hours. Lower redshift supernovae observed in $B_z$ and $V_z$ filters for every 0.1 $z$-bin would require an additional 0.9 hours and 1.3 hours per field respectively. With a 6-day $B_z$ band cadence and perfect weather, there would be time to monitor 8 fields or 56 square degrees yielding $\sim 3500$ SNe out to $z = 0.7$ in one year.

Since there is no photometric NIR component, the spectroscopic and NIR requirements can be supplied by CELT or a space telescope. All the supernovae could be followed by CELT as a $z = 0.7$ supernova would require a one hour exposure.

2. LSST + Subaru (IRCS) + CELT — The LSST can observe in the $B_z$ and $V_z$ for $z < 0.7$ SNe while $z \sim 0.8$ SNe are followed in the $V_z$-band by IRCS and in the $B_z$-band by LSST. With a 6 day cadence and $V_z$ measurements every two weeks, the LSST could survey 4 fields or 28 square degrees. The Subaru IRCS has a 1' x 1' field of view and thus can only do targeted followup of $\sim 365$ supernovae in one year. In total, $\sim 1780$ SNe at $z < 0.7$ and all $\sim 360$ supernovae discovered at $z \sim 0.8$ will be observed and followed.

   Again the spectroscopic and NIR components must be supplied by the spectrophotometry of CELT or a space telescope. All the supernovae could be followed by CELT as a $z = 0.8$ supernova would require a one hour exposure.

3. LSST + Subaru (IRCS +OHS) + CELT — No new redshift space is available with OHS but now only partial-time use of IRCS with OHS is necessary.

4. LSST + Subaru (IRCS+OHS) + AAO — To avoid the use of CELT or a space telescope, we can restrict ourselves to shallower depths. LSST can observe in the $B_z$ and $V_z$ for $z < 0.5$ SNe while Subaru obtains the NIR observations for a small subsample of supernovae. The $B_z$and $V_z$ would then require observations of 0.37 and 0.42 hours respectively for 0.1 redshift bins. With a 4 day cadence and $V_z$ measurements every two weeks, the LSST could survey 73 fields or 511 square degrees. This would amount to $\sim 16000$ SNe/year. The field of view would be then constrained by spectroscopic follow-up. A wide-field multi-object spectrograph, such as 2dF, with 3 hours per field and a cadence of 2 weeks, could follow 84 square degrees or $\sim 2700$ supernovae. A subset of $\sim 360$ supernovae would then be targeted for supplemental NIR observations at the Subaru.

5. LSST + WFC3 +CELT— LSST can observe in the $V_z$ for $z < 0.7$ SNe and $B_z$ for $z < 0.77$ SNe. The deep $B_z$ images would be used to trigger the HST $V_z$ follow-up of $0.7 < z < 1.25$ supernovae and $B_z$ follow-up at $0.77 < z < 1.25$. At least 6 points are needed for the light curve during the event lifetime, as there are at least 6 light-curve parameters we need to fit (SNAP assumes 10 points). The $V_z$-band point requires a 3.5 hour WFC3 exposure taking 57.5 hours for each $z = 1.25$ supernova. A 50% HST duty-cycle could produce 76 supernovae at $z = 1.25$. As HST obtains photometry, CELT could obtain NIR spectroscopy.

   This search will have poor quality $B_z$ observations at the early epochs of the most distant supernovae. A $z = 1.25$ SN will have $S/N = 0.9$ 2.5 mag below peak in the LSST $B_z$ image so observations can be triggered only well after explosion giving a degraded rise-time measurement and introducing Malmquist bias.

## 6. Conclusions

We find that ground-based supernova searches at the LSST can produce SNAP quality photometry, but to much shallower depths. The multiplexing advantage and the large number of SNe that can be simultaneously followed are lost when observations move away from the LSST, in particular for $B_z$ and $V_z$ observations of high-redshift supernovae, spectroscopy, and grey dust measurements.

Spectroscopy of the $z < 0.5$ supernovae could be obtained with a wide-field multi-object spec-

Table 3
Supernova Number and Redshift Range For Different Programs

| Observatories[a] | $z$ | # Fields | Scan Area ($deg^2$) | # SNe[b] |
|---|---|---|---|---|
| SNAP[c] | $\leq 1.7$ | 20 | 20 | 5600 |
| LSST + CELT | $\leq 0.7$ | 8 | 56 | 3500 |
| LSST + IRCS + CELT | $\leq 0.7$ | 4 | 28 | 1780 |
| | $\sim 0.8$ | ⋯ | targeted | 360 |
| + OHS + CELT | $\leq 0.7$ | 4 | 28 | 1780 |
| | $\sim 0.8$ | ⋯ | targeted | 360 |
| + OHS + AAO | $\leq 0.5$ | 42 | 84[d] | 2700 |
| | $\leq 0.5$ | ⋯ | targeted | 360 |
| LSST + WFC3 + CELT | $\leq 0.7$ | 4 | 28 | 1780 |
| | $\leq 1.25$ | ⋯ | targeted | 76 |

[a]Detailed description of the observatories and the search programs are found in the text.

[b]The number of supernova over all the full redshift range.

[c]The proposed reach of the SNAP satellite.

[d]Limited by spectroscopic follow-up area.

trograph. Spectra of supernovae out to $z = 1.2$ can be obtained with 10-m class telescopes. To go more distant requires adaptive optics (non-photometric!) or overwhelmingly large telescopes on the ground or a space telescope.

The grey dust measurement requirement is the most challenging within the limits of existing facilities since this requires photometric precision of faint supernovae over the bright sky background. The construction of overwhelmingly large telescopes or AO systems that are photometric would ease the burden. Additionally, significantly larger field NIR photometers (to obtain multiplexing advantage) with lower wavelength sensitivity and large-field multi-object spectrographs at good sites would improve the science reach of ground telescopes.

Coordinated efforts are necessary between several major dedicated telescopes in order to obtain the variety of data needed.

Most of the programs considered in this note would do worse than SNAP, as clearly the numbers of supernovae and especially the redshift ranges are inferior. The limiting redshifts of most of these searches barely reach the interesting transition epoch between an accelerating and decelerating universe, $z \sim 0.65$. Nevertheless, in terms of statistics and data quality, they would offer a drastic improvement over current supernova searches. The science reach of these searches, in terms of the measurement of the cosmological parameters and probing the dark energy, will be considered in a separate note.

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