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THE NEARBY SUPERNOVA FACTORY: TOWARD A HIGH-PRECISION SPECTRO-PHOTOMETRY

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Abstract. The Nearby Supernova Factory (SNfactory) is an international project to discover and study a large sample of type Ia supernovae in the redshift range $0.03 < z < 0.08$. Follow-up spectro-photometric observations are performed using the dedicated Supernovae Integral-Field Spectrograph, mounted since 2004 on 2.2 m UH telescope. The goal is to acquire for each supernova and over its full life-time (more than 10 epochs) high spectro-photometric quality spectra over the extended optical range (320–1000 nm).

I will present the current status of the SNfactory project, from search efficiency to first scientific results, with an emphasis on the spectro-photometric calibration issues and achievements.

1 Introduction

Due to their high intrinsic luminosity and their standardizable aspect, type Ia supernovæ (SNe Ia) are among the finest distance indicators for cosmology. High redshift observations played a major role in the discovery of the "dark energy" component of the universe (e.g. Leibundgut 2001 and references therein).

As expressed by Linder (2006), nearby SNe Ia (typically $z < 0.2$) play two important roles for cosmological use of the supernova distance-redshift relation: as an anchor for the Hubble diagram, and as an indicator of possible systematics. For these purposes, the author states that a "local" sample should comprise few hundreds SNe with redshifts centered on $z = 0.05$.

The spectro-photometric follow-up of this local sample will allow various studies to be undertaken with improved precision, such as:

- To calibrate the luminosity-lightcurve width ("stretch") relation, as well as intrinsic colors for dust extinction correction;
- To compute high-accuracy multi-parameters (phase, color, etc.) K-corrections, needed for photometric observations of distant SNe;
- To discover and study new spectral indicators, to derive independent estimates of intrinsic luminosity;
- To probe any potential evolutionary effects through systematic comparison of high-z SN Ia spectra with local templates;
- To improve the understanding of SN explosion physics.

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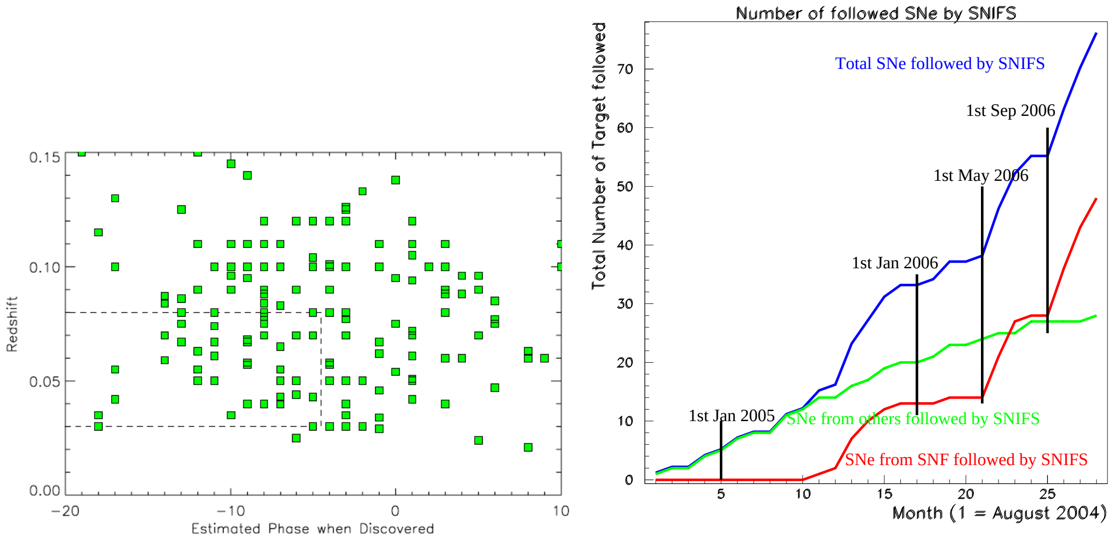

Fig. 1. *Left:* Full sample of SNe Ia discovered by the SNfactory to date. The dashed box corresponds to the optimum sample of nearby ($0.03 < z < 0.08$) SNe in the Hubble flow that are found more than 6 days before maximum. *Right:* Total number of SNe Ia followed by SNIFS (blue curve), and a breakdown by discoverer. The green curve represents the cumulative number of targets discovered by others outside the SNfactory collaboration, and the red describes the number of SNfactory-discovered SNe Ia followed up.

2 The Nearby Supernova Factory project

To address these well-defined scientific goals, the search and follow-up strategies should meet the following requirements:

- Large sample of type Ia SNe (screening and typing required) located in the low-redshift end of the "Smooth Hubble flow" ($0.03 < z < 0.08$), discovered through an unbiased search;
- Spectro-photometric follow-up observations from −15 to +45 days every 4 to 7 days, over the extended optical range (320–1000 nm) with a percent-level absolute flux calibration.

The Nearby Supernova Factory (SNfactory, Aldering et al. 2002) is an international collaboration dedicated to implement these optimal strategies. The targets are detected in unbiased wide-field images from the Palomar-QUEST Survey, using the Yale 112 CCD, 9.4 sq° camera permanently mounted on the Palomar 1.2 m Oschin telescope (Rabinowitz et al. 2003). It covers ~ 400 sq°/night, to a depth of ~ 20.5. As of July 2007, this procedure found 186 type Ia, 81 type II and 15 type Ib/c (see Fig. 1).

The selected SNe are then spectro-photometrically followed using SNIFS (see below), a fully-integrated integral field spectrograph specifically designed for semi-autonomous observation of point sources on a diffuse background. A summary of the dataset acquired with SNIFS is given in Table 1. The breakdown by discoverer is precised in Fig. 1, and the distributions of SNfactory SNe Ia screening (for type identification) and follow-up over redshifts and initial phases are shown in Fig. 2. Spectroscopically confirmed SNe discovered by the SNfactory used to be announced through Astronomer's Telegrams (~ 210 announcements), and are now available online[1] under an "open access honor system".

3 The Supernova Integral Field Spectrograph

The Supernova Integral Field Spectrograph (SNIFS) is the dedicated integral field spectrograph (IFS) used by the SNfactory for the spectro-photometric follow up of nearby SNe. It is described in Lantz et al. (2004) and

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[1] `http://snfactory.lbl.gov/snf/open_access/login.php`

Table 1. Nearby Supernova Factory data summary (as of July 2007).

Spectral epochs	Total SNe Ia	Pre-max	SNf discoveries
1+	265	123	184
6+	89	65	63
10+	76	63	50

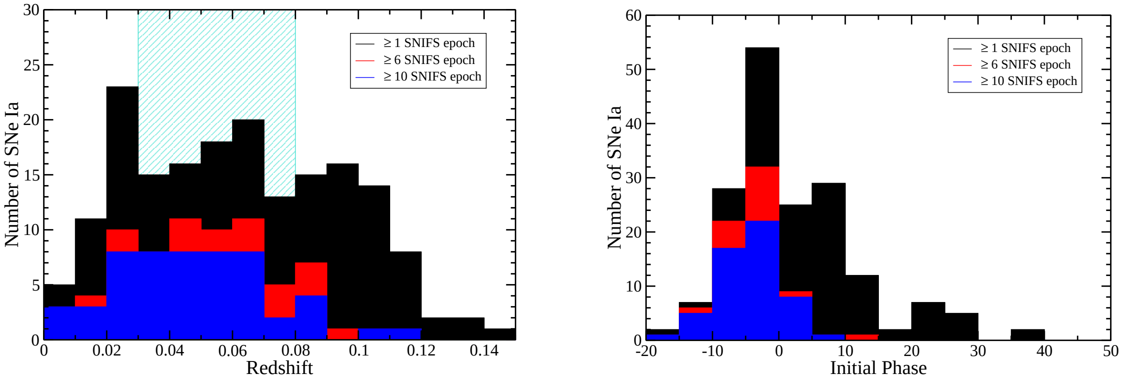

Fig. 2. Distribution of SNIFS SN Ia screening and follow-up over redshifts (*left panel*) and initial phases (*right panel*). The black histograms represent the distribution of all SNe Ia observed with SNIFS, the red histogram gives the distribution of SNe Ia observed at 6 or more epochs, and the blue gives the distribution for 10 or more observations. In the redshift histogram, the turquoise shaded region represents the target redshift range ($0.03 < z < 0.08$) in the smooth Hubble flow.

Copin et al. (2006), we summarize here the main characteristics:

- Micro-lens based spatial stage: 15 × 15 spaxels, covering a field of view (FoV) of $6'' \times 6''$ with a spatial sampling of $0\farcs42$.
- Dual channel spectral stage: channel B (320–520 nm, 2.4 Å/px) and channel R (510–1000 nm, 2.9 Å/px).
- Additional guiding and multi-filter photometric channels ($2 \times 4\farcm8 \times 9\farcm6$) located around the IFS FoV, used for target acquisition, guiding and real-time atmospheric transmission chromatic monitoring (see below).

The spectrograph is permanently mounted on the south bent Cassegrain port, and is run semi-automatically from remote locations — mainly from France and Berkeley — about three half nights per week from August 2004 to May 2006, and three full nights per week since then.

SNIFS is a relatively simple and high throughput IFS. The overall efficiency, from telescope to CCD included, reaches 18% in B, and 28% in R. Furthermore, operational overhead has been reduced to 20% through highly automated operations. This makes SNIFS a very efficient instrument on sky, which can observe more than 10 SNe per night.

4 Flux calibration scheme

The observational goal of the SNfactory is to acquire "percent-level" spectro-photometry of SNe over a decent part of their lifespan, no matter high airmass observations, moonlight, unstable atmospheric conditions and heavy clouds! This requires a very strict flux calibration scheme, which we describe now.

4.1 Photometric case

By definition, atmospheric extinction is stable during a photometric night. In this case, extinction can therefore be estimated from different spectro-photometric standard stars observed over a range of airmasses, and then used for the flux calibration of the science target.

Target accuracy requires various elements to be precisely controlled.

- It is advantageous to have an external estimate of the atmospheric stability, besides the fact that standard stars of the night form or not a flux coherent set. For that purpose, we use SkyProbe[2] (Cuillandre et al. 2002), giving a real-time estimate of the atmospheric attenuation (see an example on right panel of Fig. 3).
- The atmospheric extinction is decomposed on its physical components: Rayleigh and aerosol scatterings, ozone absorption and telluric lines (see Buton et al., this volume). It is particularly important to treat telluric component separately, because of its different airmass dependency.
- The spectro-photometric standard star spectra should be known to high accuracy, and with a spectral resolution similar to the SNIFS ones ($\sigma = 2.5$ Å in B, 3.4 Å in R), so that spectral resolution matching has only a weak impact. We selected ~ 40 well observed stars as our primary set of calibrators, with $\sim 4 \leq V \leq\sim 15$.
- The "3D point source extraction" of the standard star spectra from the IFS datacubes[3] requires a precise knowledge of the spatial PSF, dominated by the atmospheric seeing. Its large scale behavior (e.g. presence of non-gaussian wings) is of particular importance for an accurate flux estimate, since the small size of SNIFS FoV ($6'' \times 6''$) limits the usability of simpler aperture-based spectro-photometry.

4.2 Non-photometric case

Atmospheric extinction is *not* stable during a non-photometric night: $T_{\rm atm}(z, \lambda)$ depends also on t, and cannot be simply estimated from standard stars.

Since a generic atmospheric extinction curve cannot be derived for the night as a whole, one has to estimate an *effective* atmospheric extinction valid for the science observation under consideration. In SNIFS, this is done using the secondary sources acquired in the multi-filter photometric channel surrounding the IFS FoV during the science exposure. By comparing the poly-chromatic[4] flux of these sources between the current exposure and a reference exposure obtained in photometric conditions, the chromatic *differential* atmospheric extinction can be determined. In conjunction with the reference atmospheric extinction, this provides the effective curve to be used for the flux calibration of this exposure.

Note that even if SNIFS has the potential to derive chromatic differential atmospheric extinction, it appears – as it is already well known – that clouds are gray with a high level of accuracy over the full optical spectral range (see Fig. 3, see also Ivezić et al. 2007).

5 Spectro-photometric accuracy

The flux calibration scheme has been tested on the Calspec[5] fundamental primary standard GD 71 (Bohlin, 2003), observed with SNIFS in various atmospheric conditions with an attenuation of up to 0.3 mag (see Fig. 4). This results in a spectro-photometric calibration accuracy better than 2%.

High spectro-photometric accuracy requires not only a detailed flux calibration scheme, but also a thorough understanding of the instrumental details. In particular, from the IFS data reduction point of view, one faces various percent-level effects, such as CCD non-linearities, dark current sub-e^- residuals, low-level diffuse light background, inter-spectra cross-talks, humidity-related dichroic bandpass variations. These effects will impact precision mainly in the low-flux regime. Most of them are now under control in the SNfactory (diffuse light subtraction, optimal spectrum extraction, dichroic corrections), while some others (mainly CCD non-linearities) are still under scrutiny.

6 Conclusions

We presented the current status of the Nearby Supernova Factory project, an international effort aimed at discovering and obtaining detailed light-curves and spectro-photometric observations for a large sample of

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[2] `http://www.cfht.hawaii.edu/Instruments/Skyprobe/`

[3] An IFS naturally produces 3D datasets, with two spatial dimensions and one spectral dimension.

[4] The multi-filter comprises 5 selected bands representative of the different atmospheric extinction contributions.

[5] `http://www.stsci.edu/hst/observatory/cdbs/calspec.html`

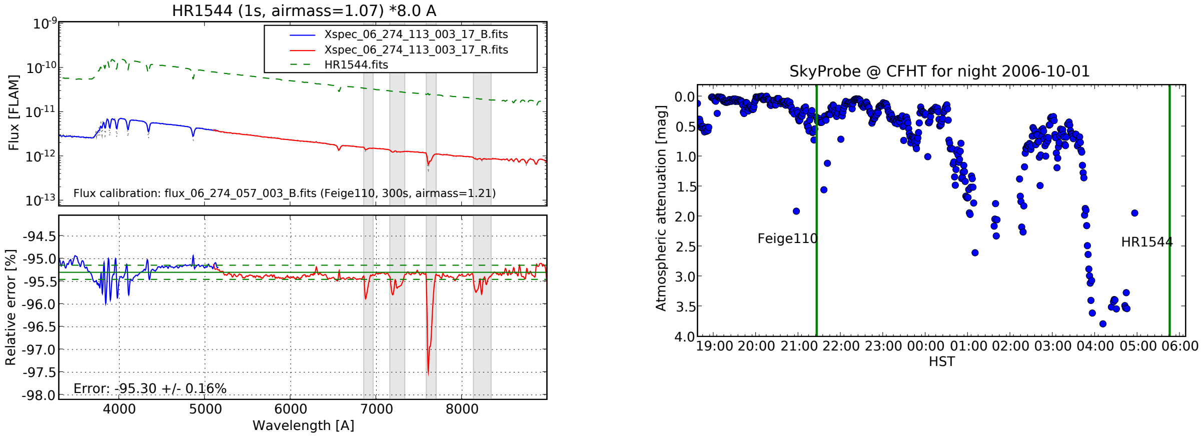

Fig. 3. Observation of secondary spectro-photometric standard star HR 1544 with SNIFS in highly extinguished conditions (night 2006/10/01). *Left:* B- and R-channel spectra (solid blue and red lines), compared to the reference flux (green dashed line, Hamuy et al. 1992). Shaded areas indicate regions impacted by telluric lines. No matter the high atmospheric attenuation (more than 95%), the extinction is gray at the 0.2% level. *Right:* atmospheric attenuation as measured by SkyProbe (Cuillandre et al. 2002) during the night. Observations of HR 1544 and Feige 110 (used as reference for flux calibration) are indicated by green lines.

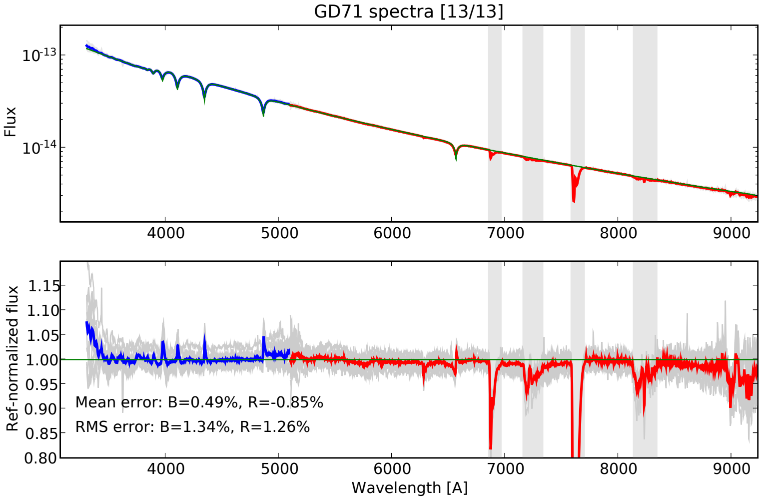

Fig. 4. Multiple observations of Calspec primary spectro-photometric standard star GD 71 with SNIFS. The star has been acquired in various atmospheric conditions, both photometric and non-photometric, with an attenuation up to 0.3 mag./airmass. *Upper panel:* F_λ spectra (gray), mean spectrum (blue and red) and Calspec reference flux (green). *Lower panel:* reference-normalized fluxes. In both B and R channels, the mean error is below 1%, and the RMS around 1.3%.

nearby SNe Ia. The SNfactory is now well under way, and will obtain $\sim$ 100 "gold" SNe Ia by end of 2007. While the accurate flux calibration scheme is subtle and requires a full understanding of the instrument, we have demonstrated that it can be achieved with a constant precision of $\sim 2\%$ in generic atmospheric conditions. It is important to acknowledge that such a precision is largely due to the proper use of the integral field spectrograph technology.

First scientific results on individual objects (the massive circumstellar envelope of SN 2005gj, Aldering et al. 2006; carbon signatures in early spectra of SN 2006D, Thomas et al. 2007) have been published, and the whole sample is now under scrutiny.

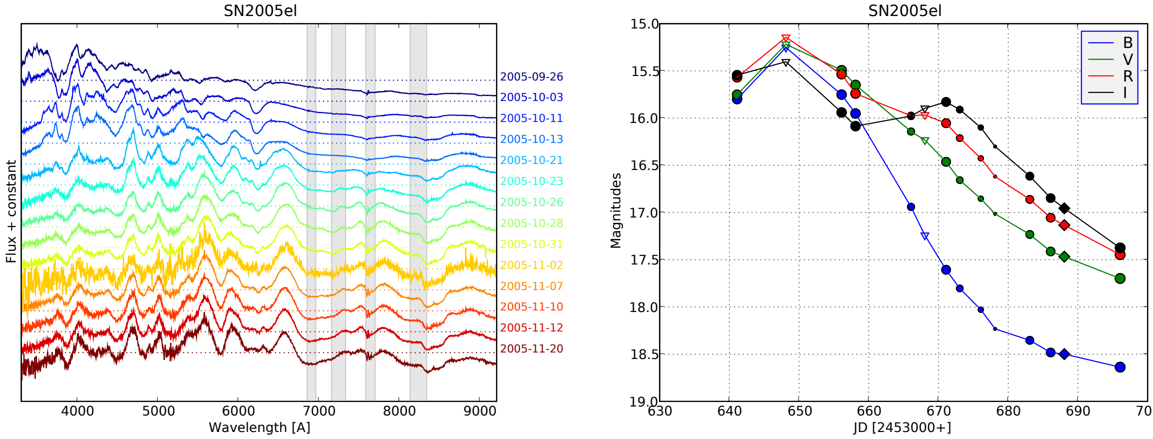

Fig. 5. Nearby supernova SN 2005el observed with SNIFS. *Left:* F_λ spectral time series, from ~ -7 to $\sim 50+$ days days with respect to B-band maximum (shaded areas indicate regions affected by telluric corrections). *Right:* reconstructed broad band ($BVRI$) light curves (diamonds: photometric conditions, dots: non-photometric conditions – smaller is worse, open triangles: unknown photometricity, treated as non-photometric).

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