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Optimizing Type Ia supernova follow-up in future dark energy surveys

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Abstract. In the next-generation supernova surveys (Palomar Transient Factory, Dark Energy Survey, LSST, JDEM, etc.) maximizing the cosmological return on each supernova and limiting the systematic uncertainties will be crucial for determining the nature of dark energy. Here we present recent results from the Nearby Supernova Factory, a program that has followed almost 200 SN Ia in the Hubble flow with spectrophotometry. We have used the code **SYNAPPS**, a combination of the **SYNOW** spectrum synthesis fitter and the **APPSPACK** optimization code to automatically perform a highly parameterized fit to observational spectra, to begin the work of identifying the spectral features in a SN Ia that are most important for using these explosions as cosmological probes.

1. Introduction

Observations of high-redshift Type Ia supernovae (SNe Ia) provided the first and to date still the best evidence for the acceleration of the expansion of the universe over the past few billion years, propelled by some kind of mysterious “dark energy,” a remarkable result that has shaken the foundations of physics [1–3]. In order to determine whether the dark energy equation of state is consistent with Einstein’s cosmological constant (Λ), enormous efforts are under way to accurately populate the SN Ia Hubble diagram with measurements of hundreds of SNe Ia at redshifts $0.2 < z < 0.8$ (e.g., the 5-year CFHT Legacy Survey and the ESSENCE program). Proposed future precision SN Ia cosmology experiments (e.g., DES, JDEM, and LSST) will work at even higher redshifts (up to $z \sim 1.7$) and/or with thousands of SNe Ia to probe the dynamical behavior of the Dark Energy equation of state.

It is crucial to remember that the SN Ia cosmology technique depends on the comparison of the apparent brightnesses of high-redshift SNe Ia to those at low-redshift to measure accurate relative distances. Moreover, our physical understanding of SNe Ia, as well as techniques for standardizing them and correcting for effects such as host galaxy dust extinction, comes from detailed observations of low-redshift SNe Ia. The utility of SNe Ia in the new era of “precision cosmology,” where the goal is to discriminate among specific models of the dark energy, depends on a more detailed understanding of SNe Ia and on methods to test for the cosmic evolution of SNe Ia and other systematic effects. To address these issues the Nearby Supernova Factory is discovering and spectrophotometrically following up a few hundred SNe Ia in the nearby smooth Hubble flow ($0.03 < z < 0.08$) [4].

The Nearby Supernova Factory (SNfactory) searches wide-field images obtained by using the QUEST-II CCD camera on the Samuel Oschin 1.2-meter telescope on Mount Palomar [5]. These

images are subtracted against older reference images to identify candidates for spectroscopic follow-up. SNfactory also operates the SuperNova Integral Field Spectrograph mounted permanently on the University of Hawaii 2.2-meter telescope on Mauna Kea for dedicated spectroscopic follow-up [6]. Our 30% time share of this facility allows us to obtain high-quality spectral time series of SNe Ia as they evolve (see figure 1). When these are flux calibrated, we can synthesize light curves from these time series in any band (see figure 2).

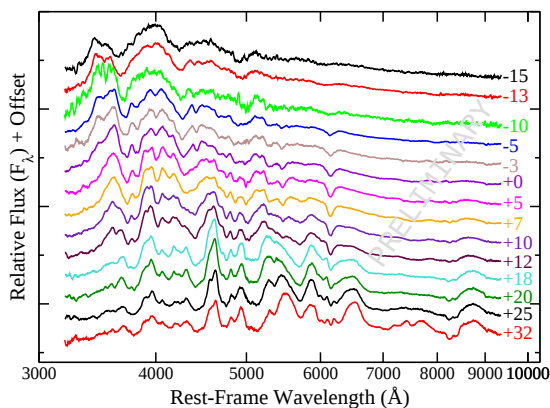


Figure 1. Spectral time series of the SN Ia SNF20070506-006, found by the SNfactory at a redshift of 0.035. Epochs are labeled wrt peak brightness in B -band.

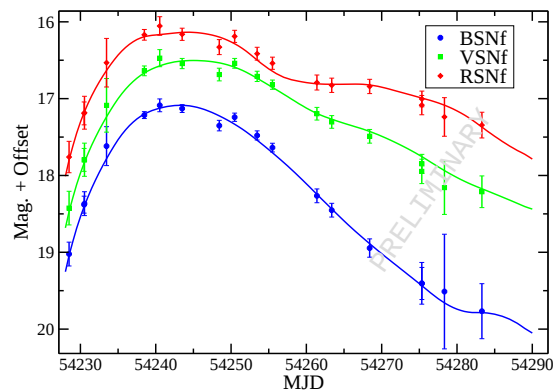


Figure 2. BVR lightcurves of SNF20070506-006 synthesized from the spectrophotometry on the left. Preliminary SALT fits are used to measure the lightcurve shape and colors.

One of the major goals of the SNfactory is to use these smooth Hubble flow SN Ia lightcurves in conjunction with higher redshift data to construct the most accurate SN Ia Hubble diagram yet, due to the augmented low-redshift SN Ia statistics and systematics control of our program. The other major goal is to search for secondary parameters in the spectra of SNe Ia that correlate with luminosity and/or reduce potential systematics in their use as cosmological probes. To achieve these goals, we turn to automated spectrum synthesis.

2. Direct analysis

SN spectra consist of blended, broad absorption and emission features on a thermal or pseudo-thermal continuum [7]. Line features in SN spectra are P Cygni profiles, consisting of a blueshifted absorption component and emission peak centered at the line rest wavelength. P Cygni profiles are typical of rapidly expanding stellar atmospheres, and typical velocities measured from the blue edge of absorption profiles in SN spectra can exceed $20,000 \text{ km s}^{-1}$. SNe evolve on timescales of days to weeks, reaching a peak absolute B magnitudes between -17 and -20 (though there are some noteworthy exceptions [8]).

One approach to the problem of reconciling hydrodynamical stellar explosion models with SN observations is semi-empirical, sometimes referred to as *direct* analysis. This data-driven technique depends on the use of fast, highly parameterized calculations of synthetic SN spectra compared directly to observed ones. A good fit to an observed spectrum constrains explosion models through spectral feature identification and characterization—the presence or absence of particular chemical elements in a SN envelope and corresponding ejecta velocity intervals. Explosion modelers take these results into account when simulating stellar explosions and nucleosynthesis.

The simplest conceptual model of a SN—applicable from a few days to months after explosion—is a sharply defined, continuum-emitting, optically thick photosphere surrounded

by an extended line-forming region optically thin to continuum. The most well-known SN direct analysis code is the highly parameterized **SYNOW** code [9], which has been used to study the spectra of SNe of all types. The Sobolev optical depth profile (as a function of velocity) is prescribed for each ion's *reference line*, usually a strong optical line. **SYNOW** uses the full Kurucz line list (more than adequate for direct analysis) and line opacity for other lines of each ion are scaled to the corresponding reference line by assuming Boltzmann excitation of the levels. The source function is that of pure resonance scattering ($S = J$); a more sophisticated source function would require a temperature structure beyond the level of parameterization that is convenient. Since reference line Sobolev optical depths are prescribed by the user individually, no physical constraint is imposed by relative ionizations of chemical elements. Still, this freedom enables one to quickly explore the parameter space of SN spectra to produce basic constraints on the underlying atmosphere.

As an example, figure 3 shows a **SYNOW** fit to the observed spectrum of the Type Ia SN 2006D around 7 days before maximum brightness [10]. This SN revealed the strongest evidence for the presence of unprocessed carbon at photospheric velocities (between 10,000 and 14,000 km s⁻¹). The ion signatures of interest are three C II lines, the strongest of which is the absorption notch around 6300 Å just to the red of the strong Si II absorption at 6100 Å. The identification of carbon with **SYNOW** in the form of a fit to three C II lines simultaneously is an important constraint on explosion models. Certain white dwarf explosion models (delayed detonations) are believed to typically burn all the carbon and oxygen fuel out to a radius of 18,000 km s⁻¹ to at least Si-peak elements [11]. In fact, the Si II feature of SN 2006D is fit well by a line profile extending to about 17,000 km s⁻¹, so the Si-peak elements somehow overlap unburned material in velocity space.

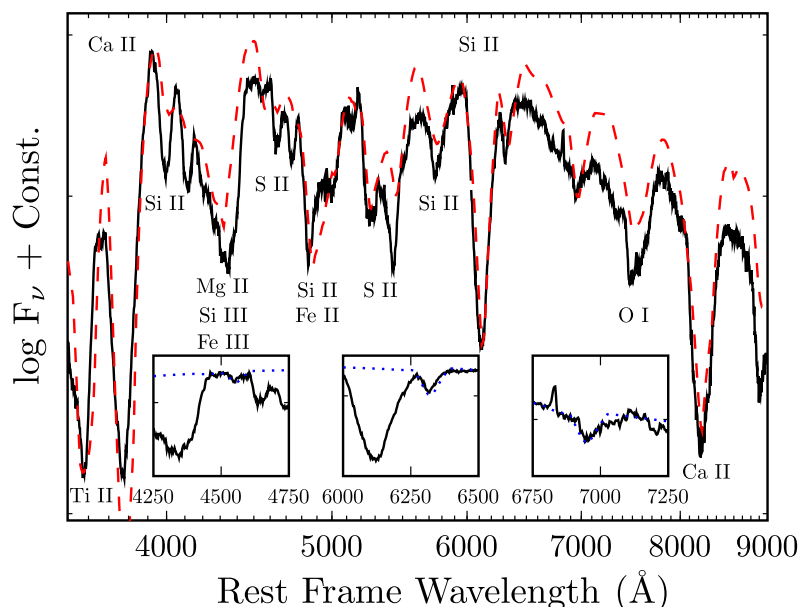


Figure 3. Direct analysis of the Type Ia SN 2006D spectrum at -7 days with respect to peak brightness. The solid black line is the observed spectrum, and the red dashed line is the synthetic **SYNOW** spectrum. The major features are mostly accounted for by various intermediate-mass and iron-peak ions. The insets again show the observed SN spectrum as a solid black line, and a single-ion simultaneous **SYNOW** fit with C II lines $\lambda\lambda$ 6745, 6580, and 7234 as the blue dotted line.

The SN 2006D results provide an instructive example. While the described constraints do not totally rule out delayed detonations, which are usually expected to completely process carbon at these velocities, they imply that nature allows for unburned material to survive, perhaps in pockets, in SNe Ia. This kind of constraint specifies parameter spaces of composition and energetics that are physically allowed for stellar explosions.

3. SYNAPPS

Until now, successful application of a direct analysis code such as **SYNOW** to observations has depended on time-consuming, human-supervised, iterative expert use. Guided by experience and rules of thumb, **SYNOW** users adjust upwards of 50 grouped input parameters to fit SN spectra. This approach has yielded useful results in the past, as discussed, but results may be subjective and homogeneous analysis of a large number of SN spectra produced by a program like the **SNfactory** and aforementioned future projects with a SN Ia cosmology component would not be feasible.

A typical **SYNOW** fit requires a human being to interactively manipulate a parameterization containing around 50 or more variables. These include what ions to include, the minimum and maximum velocities where opacity is “turned on,” how opacity changes as a function of ejection velocity, and excitation temperature. Note that, in the literature, a **SYNOW** fit is not actually a “fit” to the observed spectrum in the sense that no figure of merit is applied. The elementary SN model makes use of a sharply defined photosphere emitting a blackbody continuum, when in reality the photosphere has a wavelength-dependent boundary (if it exists at all). For this and other reasons, the theoretical continuum level is offset from the observed spectrum—a minor detail in an analysis where the goal is to simply identify lines and measure the distribution of elements in velocity space. This systematic is a nuisance in the derivation of a robust figure-of-merit, but one route is “local normalization” [12], where the spectrum is smoothed on some physically reasonable wavelength scale and the smoothed “continuum” is divided out. A simple χ^2 -minimization approach is then applied.

Each synthetic spectrum calculation takes only a few seconds once the atomic line list has been loaded. Hence, a reasonable approach to such a problem where derivatives are not easily available is a pattern search, such as the familiar downhill simplex search. Promising results have come from coupling a new spectrum synthesizer with the **APPSPACK** (asynchronous parallel pattern search) [13] minimizer package. **APPSPACK** was designed explicitly to help solve problems with up to about 100 variables on distributed architectures (though serial solutions are supported). The code coupling a direct analysis with the **APPSPACK** minimizer we call **SYNAPPS**. **SYNAPPS** uses a master-worker architecture—the master CPU generates trial points in the parameter space and communicates them to the worker CPUs, which in turn synthesize the resulting spectrum, compute the figure of merit, and report its value back to the master. Depending on various criteria such as sufficient decrease, step size, and contraction factors, the worker CPU evaluates whether the trial point is an improved fit and adjusts the list of trial points accordingly. Convergence is achieved when the trial points have converged to some neighborhood whose size is prescribed by some tolerance. We are also investigating parallelized Newton methods that may possess better convergence properties. Figure 4 includes some preliminary tests with **SYNAPPS**.

In the left panel of Figure 4, a random (locally normalized) spectrum is shown in which 10 ions are present (~ 50 parameters), and a S/N ratio of 10 per $2.5 \text{ \AA}$ bin is applied. The **SYNAPPS** code produces a successful fit to the test spectrum and finished in less than 2 hours of wall-clock time using 96 Opteron CPUs. As is often the case in optimization problems, the convergence criterion is the subject of some investigation. The best fit near χ^2/dof of 1 was found well before the code completed, indicating that the criterion could be relaxed or the initial guess improved. The input parameters were not exactly recovered by the fit, but this result is not so surprising because the parameterization of optical depth includes some degeneracies. For example, the

dependence of line strength on the opacity is roughly logarithmic, so uniformly scaling up an opacity profile can appear degenerate with decreasing its e -folding length.

The right panel of figure 4 includes a SYNAPPS fit to ground-based SN Ia spectroscopy obtained by the SNfactory. The figure shows the locally normalized SNfactory spectrum, along with the standard error. The fit to the spectrum is quite good, reproducing most of the features of the major ions. This fit took only 15 wall-clock minutes with 64 Opteron CPUs.

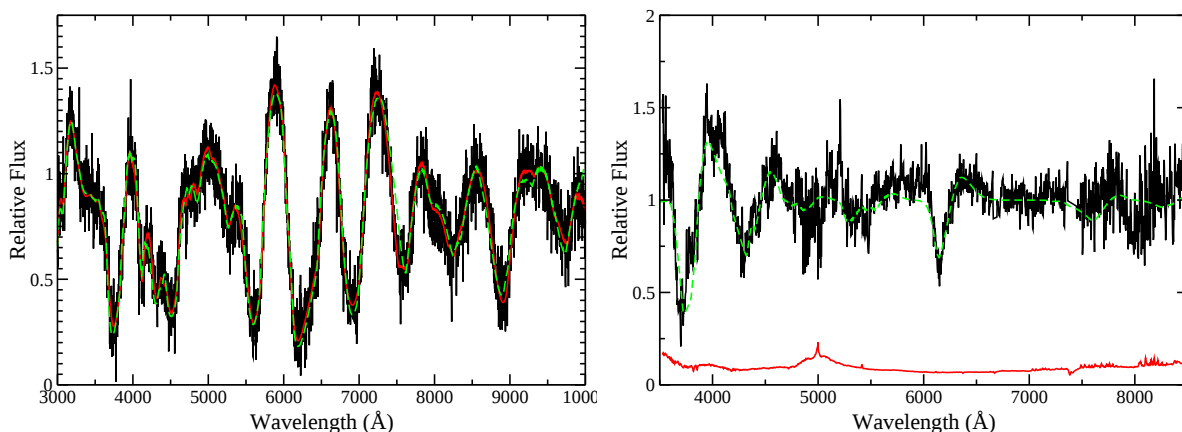


Figure 4. *Left:* Result of a 10-ion test of the SYNAPPS code. A synthetic target spectrum (the solid, noisy, black line) fit (green dashed line) with SYNAPPS using ~ 50 variables with constraints. *Right:* SYNAPPS fit to a continuum-normalized SN spectrum obtained by SNfactory. Both the observed spectrum (solid black line) and standard error (red) are plotted. The fit (green dashed line) reproduces the major features rather well. Ions Ca II, Mg II, Si II&III, O I and S II (IME ions typical of a SN Ia just prior to maximum light) were successfully identified by the code.

A further advance to the code is the recent implementation of a “penalty” function. The purpose of this function is to award the models which fit the minima of weak lines accurately (eg. the C II lines of SN 2006D mentioned above) at the cost of perfecting the fit to a very strong line. This is a generic problem for any χ^2 -minimization technique in evaluating the quality of a spectrum synthesis model. We are also working on reducing the level of model parameterization in the automated direct analysis code by replacing its *ad hoc* opacity approach with a more self-consistent calculation. This will enable automated “abundance tomography.” That is, the construction of a chemical composition and density model from self-consistent simultaneous fitting of multi-epoch spectroscopy. Again, the SNfactory data set as well as other existing data sets will be used for validation and derivation of SN models.

4. Conclusions

The automated direct analysis and abundance tomography code SYNAPPS will enable, for the first time, large-scale comparative, quantitative, homogeneous analysis of SN spectra. New composition models for SNe will be developed directly from observation for the first time. This capability is in demand now for ground-based projects engaged in the study of SN spectra and SN cosmology and will be in demand for future SN cosmology programs such as the PTF, JDEM, DES, and LSST. The SNfactory will provide more than 100 multiepoch time series of spectra to train and validate this code.

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