Draft version July 6, 2017
Preprint typeset using LaTeX style emulateapj v. 12/16/11

GENERATING AND FITTING VARIABLE AND TRANSIENT LIGHT CURVES USING SUPERNOVA LIGHT CURVE ANALYSIS SOFTWARE

Anna O'Grady
Dunlap Institute, Department of Astronomy & Astrophysics, University of Toronto, 50 St. George St., Toronto, ON M5S 3H4, Canada
(Dated: July 7, 2017)
Draft version July 6, 2017

ABSTRACT

Abstract here

1. INTRODUCTION

1.1. *Time Domain Astronomy*

The study of time domain astronomy allows us to discover new classes of variable objects, and to investigate and understand the interesting or unusual physics of known time-varying astrophysical objects. This includes many different types of sources such pulsating variable stars, eclipsing binaries, supernovae, planetary systems, and black holes. Variables and transients, in particular, have been crucial for a number of significant astronomical concepts. For example, Cepheid variables have allowed us to measure distances across the universe, from directly at galactic and Local Area scale, as well as indirectly through calibration for much larger scale distance indications. A Cepheid star existing in the same galaxy as a Type Ia supernova (SN) can constrain the luminosity of these supernovae **(Rework these two sentences)**. Supernovae themselves are vital standard candles for understanding the scale of the universe, as well as the end of stellar life cycles and feedback in galaxies **(I think?)**.

Variable and transients are both defined by a change in magnitude over a period of time. Variables undergo significant changes in apparent magnitude, usually periodic. While most stars can show small amounts of cyclic variability in their magnitude, stars specifically classified as variables are defined by much greater changes (need a number here?). Variables can be intrinsic or extrinsic in nature. The change in magnitude of intrinsic variables is a physical property of the object, for example, when a star expands and contracts and actually changes luminosity. During the expansion and contraction, the ionization and opacity of the star changes. Quasars are also intrinsic variables - these are not stars, but are the highly energetic regions around active galactic nuclei. Extrinsic variables are objects such as eclipsing binaries or planetary systems, where companions dim light on a regular basis (PercyVS). **(Don't know if I need that physical explanation anymore, might be too long)**

Transients, on the other hand, experience a large change in apparent magnitude, brightening due to an explosion or collision, and later dim to a much lower magnitude. Supernovae are a type of transient, and are an important object of study for the field of cosmology. In particular, Type Ia supernovae were instrumental in providing evidence for the acceleration of the universe (ref ref) and are still a vital component of efforts to constrain various cosmological parameters, such as the mass density of the universe Ω_m.

Much has been discovered about variables and transients though many different surveys and studies. Pan-STARRS (ref) surveys the sky at visible wavelengths in the northern hemisphere on a continuous basis, while LOFAR (ref) (and the future Square Kilometre Array (ref)) observes the sky in radio wavelengths. The All Sky Automated Survey (ASAS) (ref) searches for both variable stars and supernovae in the southern hemisphere. An example of a long period survey like this is the Digital Access to a Sky Century @ Harvard (DASCH) (ref), which could provide discrete data from over a hundred years through the digitization of photographic plates dating back to 1885. Though these surveys are expansive, there is still much to be explored regarding the physics that drives the variability of stars **(better, but still reword?)**. For example, RR Lyrae variables are excellent standard candles, but we do not understand all of the physical processes behind their periodicity **(ref, and need more?)**. There are also many types of variable and transients with interesting observed properties, but for which we know little of the physics driving their variability. Newly discovered types of transients such as luminous blue variables (LBVs) and luminous red novae (LRNe) have only a handful of objects observed to date **(refs and need more)**. To explore the underlying physics of these rare types of variables and transients, we will need surveys and telescopes capable of observing vast areas of the sky at regular intervals with excellent depth.

1.2. *The Large Synoptic Survey Telescope*

The Large Synoptic Survey Telescope (LSST) is a wide-field telescope that operates at visible wavelengths, with first light anticipated in 2021. LSST will be able to take full-sky images every 4 nights and produce over 200,000 pictures per year. The massive amount of data presents both incredible scientific opportunities and challenges. Since LSST will have full-sky images more than once per week, it will be especially well suited to the study of variables and transients. Transients like supernovae and fast radio bursts (FRBs) can be detected quickly and can be targeted for follow up observations. The LSST's location in the southern hemisphere also allows it to cover areas of the sky not seen by other full-sky surveys in the northern hemisphere.

Over its proposed ten-year run, LSST will observe tens of millions of and transients and over a hundred million variables, which will lead to important discoveries about the nature of variability, as well as improvements to measurements dependent on transient objects. The number of Type Ia supernovae, for example, that will be discovered will allow Ω_m to be significantly constrained with observations of SNe Ia as deep as $z = 1$. For variables and transients that are not supernovae, the length of LSST's observations will allow for both the discovery of many short period variables and much deeper study into the physics long period variability. The number of observations and continuity of data that LSST will provide will allow precise measurements of the light curves of many types of rare variables and transients. LSST will greatly increase the confirmed populations of many types of known variables and transients, allowing for robust population and statistical studies. It could also reveal new classes of variables, either theoretically predicted but unobserved objects or entirely new types of variables, through its ability to observe continuous, ten-year photometric light curves. Figure 1 shows the depth of LSST observations in the local universe compared to other surveys, demonstrating the enormous potential of the mission.

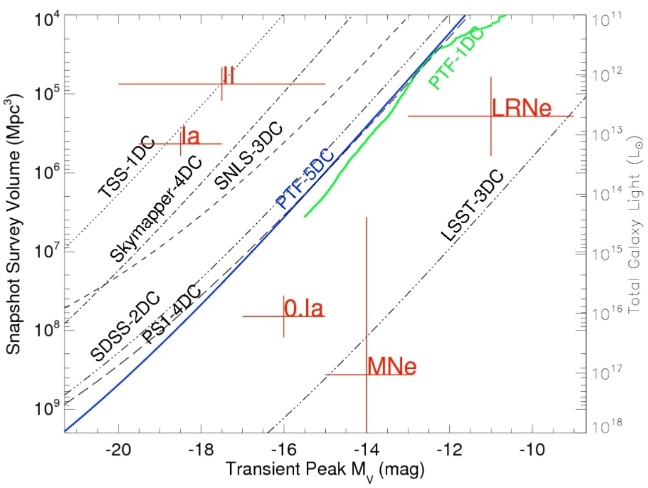

Fig. 1.— Figure 8.5 from **(LSST REF)**. This shows the depth of various surveys as a function of magnitude, with the cadence of the survey indicated by the individual labels (i.e. for LSST the cadence is 3 days). The red markers indicate the depth needed to observe that type of transient. LSST will be able to detect many rare transients within the local universe, including LRNes.

As LSST is still several years away from first-light, it is beneficial to simulate the light curves of various objects the telescope will observe in order to plan for the future of the survey. **(Bit more here to really link in?)**

2. SUPERNOVA ANALYSIS SOFTWARE (SNANA) **(SHOULD THIS BE A SUBSECTION?)**

SNANA (ref) is a general package for supernova light curve analysis. It can simulate realistic light curves accounting for weather conditions, galactic extinction, cadence, and intrinsic supernovae luminosity. It can also fit light curves to a template, and calculate cosmological parameters based on distance moduli generated from the light curve fits. In addition to constraining cosmological parameters from SNe Ia distances, SNANA can be used to examine the light curves of non Ia supernovae and improve future surveys by investigating contamination rates. The SNANA software was made publicly available to facilitate planning for future surveys, including LSST, and is designed to easily incorporate new supernova models.

The light curve simulation within SNANA creates realistic light curves by accounting for observing conditions at the area and date of the survey. Once a supernova model is chosen (two of which we will discuss below), SNANA produces the supernovae parameters related to that model. These parameters describe various aspects of the supernova, such as the time of peak brightness, color variation due to dust extinction, and the 'stretch' or shape of the light curve. These parameters are then used to calculate the magnitude of the supernova. This may involve transforming rest-frame magnitudes to observer-frame magnitudes with K-corrections, should the chosen model require this **(Do I need more of an explanation here?)**. Finally, these magnitudes are transformed to fluxes. Underlying this light curve simulator is a light curve fitter, which can generate distance moduli and redshifts of given supernovae. These parameters can then be passed to SNANA's cosmology fitter, which produces values of Ω_m and w. (ref SNANA paper)

Several different supernova models are contained within SNANA. We will briefly compare two of these - MLCS2k2 and SALT-2. MLCS2k2 and SALT-2 both are trained on existing supernovae samples, both fit parameters and light curves to given data, and both can simulate light curves from given parameters. They both have parameters related to the shape-luminosity relation and color excess in the data. In general, the light curve fits of MLCS2k2 and SALT2 are very similar. However, there are many differences between the models as well, including differences between how color variations are handled, what pre-existing data is used to train the models, and how parameters are determined. These differences are outlined in Table 1. (Main reference: Kessler et al (2009), Sections 5 and 11 in particular - https://arxiv.org/pdf/0908.4274.pdf)

SNANA was utilized in the LSST Science Book (ref) to generate example light curves of Type Ia supernovae. Here, both SALT-2 and MLCS2k2 models were used to generate the light curves, and the results were similar. They also simulated core-collapse supernovae (SNcc) with SNANA to study the contamination rates of SNcc within SNe Ia. **(Need this? Or put somewhere else?)**

Given any spectral energy distribution (SED), SNANA can generate a light curve based on that data. Thus we can use SNANA's robust light curve simulation models to fit light curves to the SEDs of variable and transient objects that may be contaminants in a survey of Type Ia supernovae, in addition to the non-Ia contaminants. Therefore, we wish to combine this existing supernovae analysis package along with templates of spectral energy distributions (SEDs) of variable objects in the literature of interest. The goal of this project is to create templates of SEDs for different types of variables and transients, then use SNANA to generate light curves from these templates. With this we can simulate, for each type of variable object, what the LSST survey will see. This could inform us about the effect of variable and transients on cosmology fits, as well as allowing us to develop a deeper understanding of the physics behind variables and transients. Are we able to tell the difference between different classifications of variables? What types variances arise

Operation	MLCS2k2	SALT-2
K-Corrections	K-Corrections are applied Shift from observer frame to rest frame	No K-Corrections No shift from observer frame
Training	Uses only low redshift SNe Uses distances from K-corr	Includes high-z SNe (Allows near-UV to be modeled) No distances used since no K-corr
Excess Color Variations	Assumed to all be due to extinction by dust (from host and MWG) or reddening	Not restricted to dust extinction, may include intrinsic variations in SNe color (red or blue)
Correlations Included	Between different epochs and passbands	Between different epochs, not different passbands
Returns	Independent distance modulus for each SNe	Global fit of distance moduli to determine SNe parameters on a global scale
Cosmological Assumptions During Fit	No, independent of cosmology, and redshift determined by spectra analysis and not included as a fit parameter	Yes, with possible uncertainties related to cosmological model and redshift

TABLE 1
DIFFERENCES BETWEEN THE SUPERNOVA MODELS MLCS2K2 AND SALT-2

when applying different light curve models to these variables and transients? Can we, generally, add something to SNANA that is more model-independent? **(Bit unsure of these 3 'questions', particularly first two)**

3. PROPOSAL

The main goal of this project is to develop something more model-independent within SNANA - to have SNANA fit light curves to variable and transient SED templates. I will be building on the knowledge of variable objects I gained through my 1501 project on a large data set of variable objects, particularly through the types of objects I will model. Quasars have very distinct colors that separate them well from other types of variables, and they also have a longer period than other intrinsic variables like Cepheids or Miras, and thus will be a good way to test how SNANA models SEDs with very long periods. RR Lyrae and Mira stars are both pulsating variables which inform us about galactic structure through globular clusters and the late stages of stellar evolution, respectively. Two more types of variables are quite rare - Luminous Blue Variables and Luminous Red Novae. Though the number of observed candidates for these types of variables are sparse, their rarity makes them an interesting target for SED modeling.

I will need to find the data to create the SEDs of these variable objects, which will show flux as a function of wavelength and epoch. This will be achieved by using variable databases, including the two-epoch long-period catalog I utilized in my 1501 project, to construct these templates. From this I will be able to generate light curves of these objects through SNANA and simulate what LSST will observe. Through the light curve fitters I will be able to parameterize the light curves of these variable objects, and the simulation will also show how variable contaminants could effect cosmology from SNe Ia also observed by LSST. **(Need more about building something into SNANA here?)**

3.1. *Initial Work*

At the start of the project, I studied the processes of the Supernovae Analysis (SNANA) software and the light curve fitters contained within. I also used SNCosmo, which uses the same light curve fitters as SNANA, to explore how supernovae light curves can be generated and fit (SNCosmo ref). An example of a simulated light curve fitting can be seen in Figure 2.

To extend SNANA's capabilities beyond SNe to different classes of variable and transient objects, I first

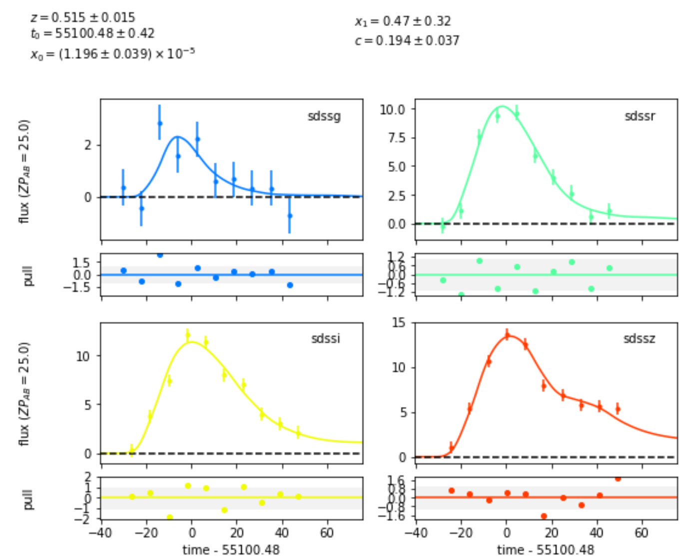

FIG. 2.— Fitted light curves of simulated supernovae in four SDSS filters, created through SNCosmo. (**More here, also need to fix formatting)**

explored the magnitude distributions of these different classes objects to identify what LSST will be able to detect. First, I worked to better understand the magnitude distributions of supernovae. I computed apparent magnitude distributions of various types of supernovae, beginning with Type Ia, and overlaying the magnitude limit of LSST. Beginning with an absolute magnitude distribution, such as those shown in (Reference paper), the apparent magnitude of any individual supernovae with an assigned redshift can be calculated. An example of this for a distribution of Type Ia supernovae and Type **(X)** supernovae can been seen in Figure (X). I will extend this to include any other variable and transient objects for which there is a reasonably modern absolute magnitude distribution available.

My next steps include installing and running SNANA to understand how its simulations and fitters work, and beginning to construct the spectral energy distributions for the chosen variables and transients for integration into SNANA.

4. TIMELINE

Below is an approximate timeline for the completion of this project. Red items are major events within the scope of 1500, violet items are work already completed, and blue items are important events not directly related to 1500.

- Weekly: Meetings with supervisor

1. Early June: Protect started, began with reading literature on supernovae, SNANA, and the light curve fitters MLCS2k2 and SALT-2.
2. Late June: Began work on magnitude distribution and proposal.
3. July 7: Proposal Submission
4. Early July: Finish magnitude distribution code.
5. Late July: Collect data for the creation of variable spectral energy distributions; install and run SNANA for various SNe.
6. July 31: Progress Report 1
7. August: Begin to create light curves from the SEDs in SNANA, fitting them with MLCS2k2 or SALT-2, to simulate variables that will be found by LSST.
8. August 31: Progress Report 2
9. Early September: Classes, TA duties, and early thesis work begins.
10. September: Finish LSST survey simulation with SNANA. If possible, examine how the variable contaminants will effect the resulting cosmology from SNe Ia in LSST.
11. Mid September: Begin writing final report.
12. September 30: Progress Report 3
13. : October: Write final report and create final presentation.
14. Mid October: Final Presentation
15. October 31: Final Report Due