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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
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ABSTRACT

Abstract here

1. INTRODUCTION

1.1. *Time Domain Astronomy*

- Why variables are interesting and important. Actually could probably call this as another 'Time Domain' thing again, I suppose?
- There are some we know so little about. Even include the 'this is what variables are' thing, and indicate that supernovae are a type of transient. They fall into their own category because they are particularly relevant for cosmology whereas other types of variables and transients are not, but SNe are still technically transients.
- Here I explain time domain astronomy and why it is interesting, what it tells us. Probably talk about some of the open questions and interesting objects, like LBVs. Also any constraints on the field, specifically whichever constraints LSST will open up.
- This is the 'big picture' section, i.e. why my project is important.

Need an actual intro sentence. Variables and transients have been crucial for a number of significant astronomical concepts. Variable stars such as Cepheids 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 existing in the same galaxy as a type Ia supernova (SN) can constrain the luminosity of these supernovae. 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?).

Though much has been discovered about variables and transients though surveys and studies such as (EXAMPLES), there are many avenues which have not been explored (rework this entire sentence). For example, RR Lyrae variables are also good standard candles, but we do not understand all of the physical processes behind their periodicity (don't know if I should include this).

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). While these objects undergo a change in apparent magnitude, the physical luminosity of the individual objects does not change, differing them from intrinsic variables. **(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. **(Bit here about constraining cosmological parameters, reference the Nobel papers?)**

There are many types of variable and transients with interesting observed properties, but for which we know little of the physics driving their variability. New types of transients such as luminous blue variables (LBVs) and luminous red novae (LRNe) have only a handful of objects observed to date. **Need more here, and a specific link to LSST**

1.2. *The Large Synoptic Survey Telescope*

- The relevancy of LSST - what it is, what it will do specifically for variables, and what we need to work with this massive amount of data
- We want to use existing SN analysis software to try and work towards something more model independent that can fit light curves to variable templates and therefore produce sample light curves (right?)
- Explain what LSST is here, what advances it will bring.
- In here, at the end, I'll need to link this information to what I'll actually be doing for the project. I need a nice transition from LSST and what it does with var/trans, to what it does with SNe and using SNANA, to then get into how we'll use both.

The Large Synoptic Survey Telescope (LSST) is a wide-field telescope 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 noticed quickly all across the sky and can be targeted for follow up observations. Also, its location in the southern hemisphere allows it to cover areas of the sky not seen by other full-sky surveys in the northern hemisphere such as CHIME.

Over its proposed ten-year run, LSST will observe tens of millions of and transients and over a hundred million variables. The number of Type Ia supernovae, in particular, that will be discovered will allow Ω_m to be constrained with observations 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. While LSST will not operate on the timescale of other long period variability projects, such as the Digital Access to a Sky Century at Harvard (DASCH) (ref), the number of observations and continuity of data 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.

Over the next ten years LSST will produce incredible large amounts of data on short timescales, and we must have the technical skills and physical understanding of the types of objects we may detect to be able to handle this data. From (LSST ref), we will be seeing tens of thousands of variables and transients each night with LSST. **Need stuff here about quick classification? Or is this way too technical? Am I talking too much about LSST?**

Can I show a Figure from a different paper here? Fig 8.1/8.5 in the LSST Science book are pretty nice since they talk about specific types of interesting variables discoverable by LSST.

To end this, I think I need to make some kind of connection between LSST seeing lots of SNe and LSST seeing lots of var/trans? I need some reason to start talking about SNANA in the context of variables

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

SNANA (ref) can generate 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.

Several different light curve fitters are contained within SNANA. We will briefly compare two of these - MLCS2k2 and SALT2. **(NOT going to keep all of this, just a placeholder for the moment, will probably fit into a table**

– MLCS2k2 and SALT2 both are trained on existing supernovae samples, fit parameters and light curves to given data, and 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.

In MLCS2k2, K-corrections must be applied to correct the observations for redshifted supernovae. This involves shifting from observer frame filters to rest frame filters. However, in SALT2, the data are not shifted to rest frame filters.

In the training process, MLCS2k2 only uses low-z (low redshift) supernova, while SALT2 includes high-z supernova in order to model the near-ultraviolet area of supernova spectra. Since K-correction is not done, SALT2 does not make use of any distances in the training process.

Any excess color variations in the MLCS2k2 model are assumed to all be due to extinction by dust (in both the host galaxy and our Milky Way), or reddening. In SALT2, color variation is not restricted to dust extinction, and may include intrinsic variations in the supernova color or other effects which may cause redder or bluer colors.

In MLCS2k2, correlations between different epochs and passbands, while SALT2 only includes covariances between different epochs in the same passbands, but not between different passbands.

MLCS2k2 returns a distance modulus (with errors) and does not make any cosmological assumptions during the fitting process. The redshift is determined from the spectroscopic analysis, and is not included as a fit parameters. SALT2, however, does not give an independent distance modulus for each individual supernova. Instead, cosmological parameters are included as part of a global fit of distance moduli to determine supernova parameters on a global scale. This can introduce uncertainties related to the cosmological model and redshift.

(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 SALT2 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.

Show an SNCosmo fit here, for a figure?

We wish to combine this existing supernovae analysis package along with templates of spectral energy distributions (SEDs) of variable objects in the literature. The goal of this project is to create templates of SEDs for different types of variables and transients, use SNANA to simulate light curves, then fit (or deform) these light curves to the variable and transient templates. Are we able to tell the difference between different classifications of variables? Can we construct or work towards something more model independent?

3. PROPOSAL

- What steps we're actually taking to move towards this goal.
- We also want to try applying cosmology to these objects.
- Will describe specifically what variables we want to look at (LBVs are an easy first choice).
- In the work done section, talk about the mag histograms and redshift limit, including a FIGURE here of one of them. Then describe that we will perform this same thing but for variables and transients for which we have magnitude distributions, **so we can see which kinds of variables LSST is actually going to pick up**.
- The thing we're eventually working towards is to be able to fit SNANA light curves to our templates of variables and transients. The first step of this is going to be building the SED templates for different variables.
- I can make a link to my 1501 work, maybe?
- We want to work towards something more model-independent with SNANA, and have it be able to generate and fit light curves to variable and transient SED templates.
- I need a clearer picture of what the future parts of the project will be. I know what I'm doing now, but I need a bit more detail on what the major steps will be so I can detail them here. Within this, also need to talk about making sure the project isn't too open ended.

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.

(Need some kind of actual flow into this part) We wish to explore the magnitude distributions of different classes of variable objects to identify which kinds of variable and transients LSST will be able to detect. First, we compute 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 can been seen in Figure (X). We will extend this to include any other variable and transient objects for which there is a reasonably modern absolute magnitude distribution available.

The main goal of this project is to work towards something more model-independent within SNANA - to have SNANA generate and fit light curves to variable and transient SED templates. To that end, we will be...

4. TIMELINE

Below is an approximate timeline for the completion of this project. Red items are major events within the scope of 1500, magenta 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: ?
6. July 31: Progress Report 1
7. August: ?
8. August 31: Progress Report 2
9. Early September: Classes, TA duties, and early thesis work begins.
10. September: ?
11. Late September: Begin writing final report.
12. September 30: Progress Report 3
13. : October: ?
14. Mid October: Final Presentation
15. October 31: Final Report Due