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

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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, 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 star 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?).

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?)**

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. New 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, liiiiink **(specific link to LSST)**

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. 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 the Canadian Hydrogen Intensity Mapping Experiment (CHIME) (ref).

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, or the mass density of the universe, to be 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.

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) 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 the constraining of cosmological parameters from SNe Ia distances, SNANA can be used to examine the light curves of other types of supernovae and improve future surveys by investigating contamination rates.

(Here I will explain just generally how SNANA works

Several different light curve fitters 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.

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. **SN Cosmo figure here?**

(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

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 light curve fitters MLCS2k2 and SALT-2

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