Comparing lightcurves of SN2014J to SN1987A between cooling phase and Nickel-56 peak

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1 Abstract

When a supernova explodes, the matter of the star is ripped apart with such force that even neutrons are ripped from protons. As the expanding cloud cools, the matter forms into ^{56}Ni, a relatively stable atom. ^{56}Ni decays over time into ^{56}Co, then ^{56}Fe. Each of step of this decay process releases gamma rays, which deposit energy into the surrounging gas, "propping up" the supernova's luminosity.

Preceding the peak of ^{56}Ni and thus luminosity in the supernova and after the drop in luminosity due to cooling, Type Ia supernovae like SN2014J and Type II-P supernovae like 1987A differ significantly. Here we compare example lightcurves from each category and discuss implications for how the supernovae explode and how we decide taxonomy.

2 Background and Data

The taxonomy of supernovae is, like that of planets, a system which has developed over many years as we creep intellectually through the cosmos. It is not based directly on progenitors, which we still can only feel towards in some cases, nor on explosion mechanism, the specifics of which continue to elude us. Instead, supernovae are categorized by what is simple to observe from our rock: their spectra.

First supernovae are split into Type I and Type II supernovae. Type I supernovae do not contain hydrogen – that is, we do not observe H's spectral lines in their photometry. Type II supernovae do exhibit H spectral lines [3].

Type I is further divided into Type Ia, Ib, and Ic. Type Ia supernovae have silicon spectral lines. Type Ib has no silicon or hydrogen, but helium. Type Ic has no silicon, no hydrogen, and no helium at all. Type II is divided into Type IIn, IIP, IIL, and IIb. Type IIn exhibits hydrogen, as all Type II's do, but their lines are narrowed, indicating that the hydrogen was moving slower than normal. Astronomers argue this is caused by the ejection of the hydrogen before explosion, which has been substantiated by some observation. Type IIP supernovae don't differ in ingredients, but they remain at their peak (plateau) before a gradual ^{5}6Ni-controlled descent longer than other supernovae. Type IIL have the normal ingredients, but drop rapidly and linearly after peak. Type IIb spectra change fundamentally over time: early in the explosion hydrogen can be observed, but later these spectral lines shrink and vanish from the spectra [3].

Spectra are our first and dearest friends in astronomical observation. To deduce how supernovae explode and what they explode from, lightcurves provide essential information to constrain computer models of the explosion. With this interest. we compare the pre-plateau lightcurves of two supernovae: 2014J, a Type Ia, and 1987A, a Type IIP. We plot magnitude vs. time for each band individually, all bands together, and compare linear fits for the rise from cooling trough to brightness plateau.

3 Type Ia Example: 2014J

The mechanisms of Type Ia supernovae are, like most other supernovae, only gestured at by modern astrophysics; we can guess some of what happens, but the exact mechanisms of the explosion and progenitors remain mysterious. What we do know is that Type Ia lightcurves are remarkably consistent. They have the steepest climb to the ^{56}Ni plateau of all the types, post-cooling [1]. We plot this range here for SN2014J: first band by band, then with all the bands compared together.

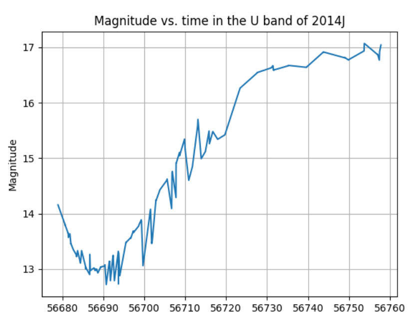

Figure 1: Change in brightness of SN2014J across time in the U band.

4 TypeII-b Example: 1987A

Type II-P supernovae starkly contrast with the quick rise-and-drop in magnitude of other supernovae before ^{56}Ni beta decay takes hold of the magnitude. Type II-L supernovae exhibit lightcurves very similar to those of Type Ias, but II-Ps show unusual slow rises and relatively flat plateaus that can stretch to 100 days

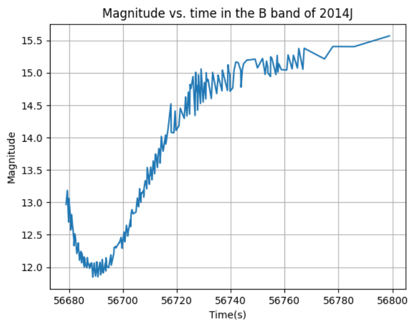

Figure 2: Change in brightness of SN2014J across time in the B band.

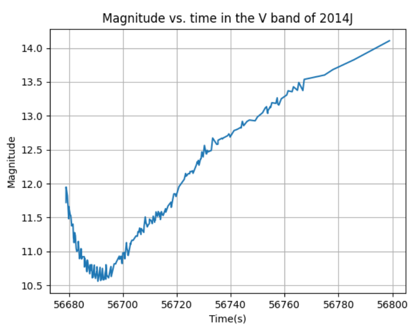

Figure 3: Change in brightness of SN2014J across time in the V band.

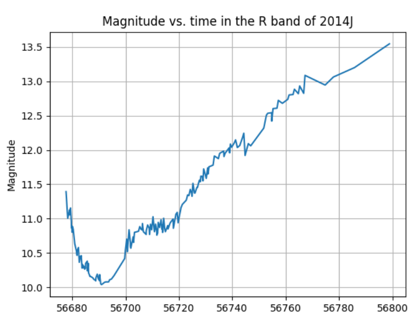

Figure 4: Change in brightness of SN2014J across time in the R band.

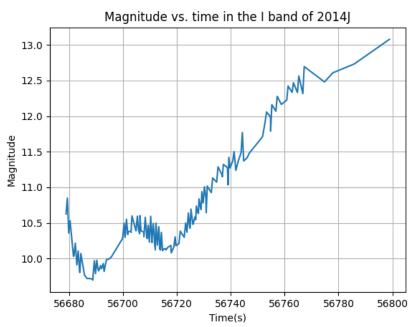

Figure 5: Change in brightness of SN2014J aross time in the I band.

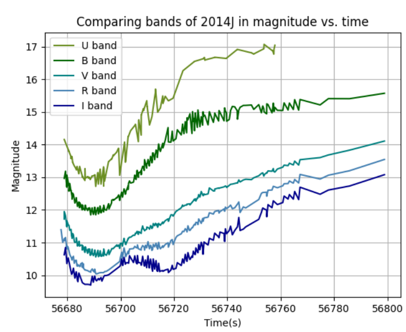

Figure 6: All bands of SN2014J together. Note especially the differences between the shape of the I band brightness over time compared to the bluer colors. Just before 56720 seconds, a "shoulder" is visible in the curve. Its beginnings show up in the R band as well.

or more [2]. Here we plot magnitude versus time for five bands of 1987A, the quintessential Type II-P supernova, with special attention to its pre-plateau shape.

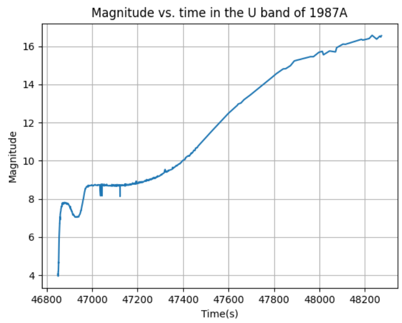

Figure 7: Change in brightness of SN1987A across time in the U band.

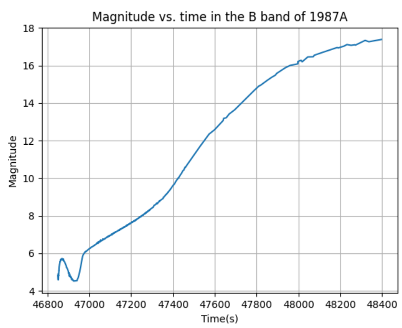

Figure 8: Change in brightness of SN1987A across time in the B band.

5 Lightcurve Comparison

From these magnitude vs. time plots, we can calculate a linear fit to the climb between cooling trough and plateau. This provides a quick comparison for how quickly the brightness rises to the plateau in the first moments of the supernovae.

Below are plots of the U band of 1987A and 2014J with a linear fit. The U band has been selected because in both lightcurves, its rise is very linear and free of the ”shoulder” observed in the 2014J spectrum. For both supernovae, a range has been selected to focus only on the specific, initial climb. For 1987A, this is 47400 through 47800 seconds. For 2014J, this is 56700 through 56720 seconds.

This slope may be described by the following equation:

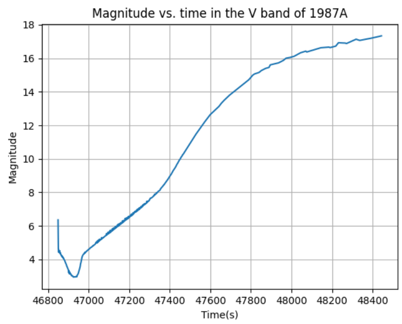

Figure 9: Change in brightness of SN1987A across time in the V band.

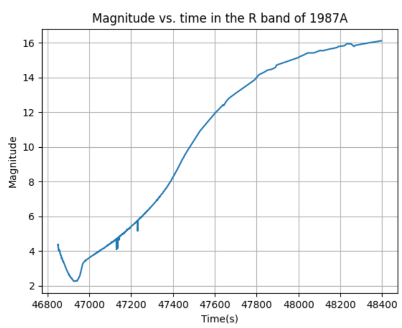

Figure 10: Change in brightness of SN1987A across time in the R band.

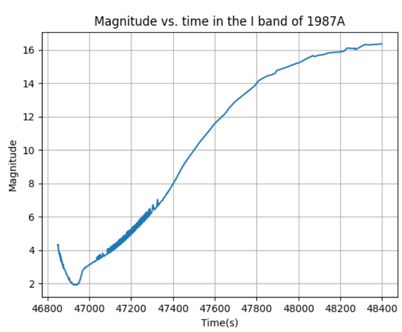

Figure 11: Change in brightness of SN1987A aross time in the I band.

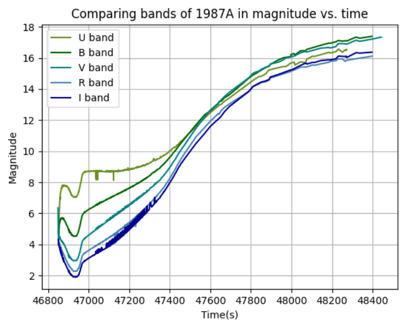

Figure 12: All bands of SN1987A together. Note the similarity in magnitude vs. time curve of each of the five bands, as opposed to the distinct differences between bands observed in 2014J.

$$fit = m * t + b \tag{1}$$

where the fit is the linear approximation of the lightcurve in this specific range, m is the slope, t is time in seconds, and b is the intercept with the magnitude axis. It is important to note that equation (2) is first-order only, and thus is a very simple approximation of lightcurve.

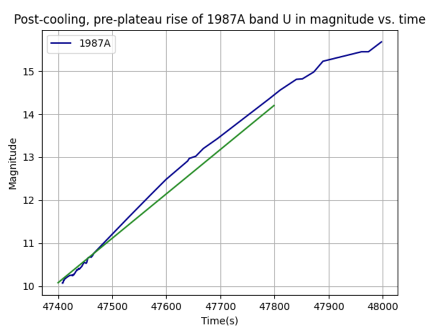

Figure 13: Linear fit to magnitude vs. time in U band of 1987A. Slope for 1987A = 0.0103319.

From these plots, we observe a slope of 0.0103319 for the U band of 1987A and a slope of 0.0975568 for the U band of 2014J. This difference fits our expectations based on the typical lightcurves of Type IIP and Type Ia supernovae: Type Ia tend to rise in brightness much more sharply at the start, while Type IIP climb more slowly. 1987A and 2014J are typical examples of this feature.

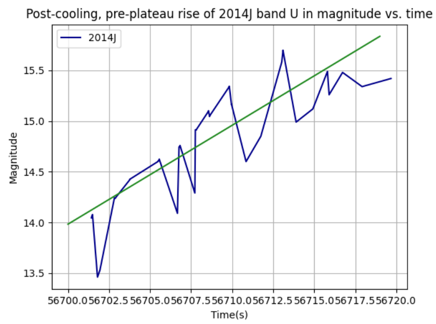

Figure 14: Linear fit to magnitude vs. time in U band of 1987A. Slope for 2014J = 0.0975568.

6 Calculating area with the trapezoidal methods

In instances where analytical integration is inefficient or impossible, numerical integration allows us to get pretty dang close (scientific term) to the correct answer. There's a variety of methods for numerical integration, each with different accuracies and executing efficiencies, but for our purposes here we have selected the trapezoidal method of integration.

Using the trapezoidal methods for estimating integration, we can find the area beneath these magnitude vs. time curves. It's important to note that because the data is *magnitude*, a constructed unit, and not luminosity, this integration doesn't clue us in to any physically significant information. Still, this method is an interesting demonstration of the trapezoidal integration method.

This method can be boiled down to finding the area of a smallest-possible trapezoid beneath the curve, with corners at x[i], x[i+1], y[i], and y[i+1]. Here our x is time and our y is magnitude. The counter variable i allows us to step through the data each x,y pair at a time. The equation used is

$$totalarea+ = (time[i+1]-time[i])*0.5*(magnitude[i+1]+magnitude[i]) \quad (2)$$

for each i.

For each filter of 1987A and 2014J, the total area was calculated using this equation and the numpy.trapz function. The results and the computation times between the two methods are compared. Below are the tabulated results:

Data set	Area with eq.	Area with np.trapz	Time with eq.	Time with np.trapz
1987A B	18681.23524000001	18681.235240000016	0.504	0.511
1987A I	16272.21509499989	16272.21509499999	0.497	0.509
1987A R	16500.97514499999	16500.975144999986	0.517	0.514
1987A U	17102.96229000001	17102.962290000014	0.509	0.527
1987A V	18689.896174999987	18689.89617499999	0.508	0.513
2014J B	1720.4177646009648	1720.4177646009646	0.516	0.498
2014J I	1362.3374054999867	1362.3374054999846	0.498	0.524
2014J R	1437.7346721034650	1437.7346721034646	0.583	0.511
2014J U	1207.299325404308	1207.299325404308	0.504	0.499
2014J V	1499.9410649607576	1499.9410649607576	0.509	0.510

Because np.trapz is written in lower-level languages like C or Fortran, it is compiled to run, rather than interpreted like a Python script. Typically, compiled scripts run lightning fast compared to interpreted languages. Above we observe instances of both the equation script running in less time and np.trapz running in less time; it's important to note that the execution time varied wildly between each iteration. For example, for the same script with the same commands, we observe a deviation of execution times of more than half a second.

When composing code, efficiency is a balance between development time and execution time. Complexity of the solution, frequency with which the script will be run, and time and precision constraints are all important factors. High-level langauges like Python are, for most developers, faster and easier to write in: it's closer visually and grammatically to human languages, and thus it's less effort to "think" in high-level languages. Low-level languages execute more quickly, but are slower to write with more propensity for small, nearly inscrutable errors. Functions like trapz in modules like numpy are a useful compromise: referencing quick, low-level scripts with the readability of high-level languages.

7 Summary

Our current system for the classification of supernovae can be cumbersome and inefficient as our understanding of these events increases. Type IIb, for example, exhibits features of multiple categories. Still, these categories generally describe features of supernovae that can be gathered at a glance: spectral features, plateau shape, or the steepness of the rise and fall of brightness. For now they are useful. Future discoveries about the explosion mechanisms and progenitors of supernovae may present a new, more direct and intuitive taxonomic system. The astronomy community must be willing to adapt our categories with our understanding as we explore the cosmos.

References

[1] Type ia supernova light curves: Cosmos.

[2] Tomasz Nowakowski. Astronomers investigate type iip supernova with a long plateau, Jun 2018.

[3] Ashley Villar. Classifying supernovae, Dec 2016.