

ANALYSIS OF SUPERNOVA PHOTOSPHERIC VELOCITIES

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Analysis of Supernova Photospheric Velocities

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A series of scripts were created in Python to isolate and measure the Si II absorption line feature in the spectra of Type Ia supernovae. This line feature was then compared to the rest wavelength of Si II, and using the Doppler Shift equation, the photospheric velocities of the supernovae were determined. For each supernova studied, this procedure was repeated over various spectra taken at various times, which were then plotted relative to the day of maximum brightness for the individual supernova, and the data was fitted to a regression line. The photospheric velocities for the day of maximum brightness and the gradient of photospheric velocity decline were recorded and compared between supernovae, and the intrinsic color of the supernovae was compared using this data. The results indicate that the photospheric velocity at the day of maximum brightness correlates positively with the steepness of the slope of the velocity decline gradient. The photospheric velocity at peak was also compared with color and the results indicate that the correlation is negative.

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Contributors

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1. INTRODUCTION

1.1 Type Ia Supernovae

Astronomers are able to observe a variety of celestial objects in the heavens, from nearby stars and planets, to galaxies millions of light years away. When observing other galaxies, one class of object is particularly noteworthy and important: supernovae. Of the various types of supernovae observed, this paper shall focus on one in particular, that being Type Ia supernovae. In particular, I determined the photospheric velocity of several Type Ia supernovae, how the velocity changes over time, and any correlations these values may have.

The term "supernova" applies to a variety of stellar objects that are undergoing the process of death, generally a rather violent one, characterized by an explosive release of matter and light. According to L. A. L. Da Silva in his 1993 paper "Classification of supernova", supernovae are caused by the death of a degenerate star [1]. A star becomes degenerate when its mass exceeds the Chandrasekhar limit, causing the core of the star to become unstable. When this occurs, the star is no longer able to maintain its size or shape, and it releases mass in an explosive event referred to as core collapse. In this situation, it is not uncommon for the collapsing star to steal the mass from objects within its celestially close proximity. When the collapsing star is a Carbon-Oxygen white dwarf, this process of collapse and explosion is referred to as a Type Ia supernova. Because of the unique properties of Type Ia supernovae, this project will focus on them exclusively.

1.2 Cosmology and Distances

Type Ia supernovae are important for the field of cosmology and for calculating the distance to celestial objects [2]. Because of the nature of their explosive formation, Type Ia supernovae tend to have fairly predictable features and spectrum. This data, when properly calibrated to account for dust and red-shift, can be used to measure the astronomical distance from the Earth to the supernova. Furthermore, supernovae provide an excellent source of data for cosmological models and for predictions related to the life cycles of stars.

1.3 Spectrum

In astronomy, a spectrum is the shape of the light curve of an object. When objects reach a certain temperature, they begin to release light. At high enough temperatures, such as those obtained by stars, galaxies, and supernovae, the light released ideally tends to follow a black body curve. In reality, however, it is not that simple. When an element gains energy, it enters an excited state. To return to its normal state, or ground state, the atom must release energy. Because of quantum mechanics, atoms can only release this energy at particular values. When an atom releases energy, it does so by emitting light at different energy levels, each of which corresponds to a specific color. Because of their structure, each type of element can only release light with certain wavelengths, with the particular wavelengths that an element can release being referred to as the emission lines of that element. A similar concept applies in reverse: each atom can only absorb energy at discrete values, creating the absorption lines of the element.

For stellar objects, their spectrum is a combination of the black body curve, called a continuum, and the emission and absorption lines. Because of object motion and mechanics, the emission and absorption lines are offset from each other in a sort of sideways "S" shape, called a P-Cygni distribution, which is characteristic of expanding objects [3]. Because each element's lines occur at different locations, the wavelength at which we find a feature can be used to determine important information about the supernovae, such as the velocity or color. For Type Ia supernovae, one absorption line of extreme importance is the silicon II (Si II) absorption line, which has a rest wavelength of 6355\AA . The Si II line is present in nearly all Type Ia supernovae, making it a useful tool when studying them, particularly their photosphere and its features.

1.4 Photosphere

The photosphere of a supernova, and its properties, are very important concepts in astronomy. A photosphere is the layer at the deepest depth into a stellar object that can be observed [3]. Much like a pool of water, you are only able to see so deeply into a star or supernovae before it is too dense to see through. Because the supernova expands over the course of its explosion, the exact depth of the photosphere is not constant, and it can be said to "move." For this project, I

studied the photospheric velocity, which is a measure of how quickly the photosphere is moving. To do so I used the Si II lines of the spectrum, because Si II makes up part of the surface of the photosphere. By determining its velocity, I can also determine the velocity of the photosphere.

1.5 Velocity and Color

When an atom is moving its energy is different than if it were stationary, causing it to absorb and release light at different wavelength. The wavelengths of light for a stationary object is called the rest wavelength. For Si II, the rest wavelength of the absorption line is 6355\AA . To determine the velocity of the photosphere, I compared this rest wavelength to the measured wavelength and used the Doppler Shift equation, as detailed below. This velocity is often referred to as the photospheric velocity, and it is an extremely important value when studying supernovae, as is how it changes over time.

The photospheric velocity is related to another important quality of a supernovae: its intrinsic color. Color in astronomy is not the same as color in everyday conversation. Astronomers measure light, and how much light is produced in certain ranges of wavelengths, called bands. A color is the difference between the amount of light detected in two bands. For example, the $B - V$ color of a supernova is the amount of light in the B-band minus the amount of light in the V-band. These colors are highly dependent on the temperature of the object, and the spectrum can be used to determine these colors. Color is useful because it can be used to determine the distance to an object.

Once the intrinsic color of the supernova is determined, it can be used to calculate the extinction. Extinction refers to the effect that dust in space has on light. When light passes through dust, some of the light is lost to absorption, often at specific wavelengths, based on the composition of the dust. If we know the color of a supernova, we can compare the measured and theoretical values to calculate how much light is lost to dust, allowing us to then correct for that dust in other observations. This is particularly important for other astronomers looking to observe through these dust clouds, especially in bands that are heavily affected by the dust, including the ultraviolet band of light.

1.6 Day of Maximum Brightness

Because of the importance of supernovae for measurements, it is often necessary to compare properties between them. No two supernovae are the exact same, so astronomers often use features or qualities that are constant across nearly all supernovae. The previously mentioned Si II absorption line is one such feature for Type Ia supernovae. To determine the photospheric velocity as a function of time I used another such trait: the day of maximum brightness. When a supernova explodes, it gradually becomes brighter before dimming as the reactive materials are ejected or consumed. This gives a day of maximum brightness for the supernova, and since all supernovae reactions proceed in such a manner, each will have a day of maximum brightness. When I plotted the photospheric velocity as a function of time, I set this date as the zero point on my time axis, and I used the velocity at this date for comparisons between supernovae. Further, I focused my efforts on the days around the Day of Maximum Brightness, or the Peak. Because the change in brightness resembles a curve, the changes in the photospheric velocity will not be linear over the entire lifetime of a supernova. Instead of looking over the entire length of the supernova duration, I limited my search to the twenty days before and after the day of maximum brightness.

1.7 Python

To perform the analysis, calculations and data plotting needed for this project, I used the coding language Python. Python is an open source code platform, allowing anyone to create programs and procedures, referred to as scripts. A collection of Python scripts is referred to as a code library. There are a multitude of Python code libraries available for free online, and I used several of these libraries to create the code I used in this project. For the computations and calculations, I used the math based libraries "numpy," "pandas," and "math." To work with astronomical data, and to analyze that data, I used "astropy" and "specutils." For my plots, I used "scipy" and "matplotlib" and I determined the uncertainty of my results using "linmix" and "scipy." Other miscellaneous libraries I used are as follows: "os" to read in my data and "warnings" to disable warning messages.

1.8 Project Overview

The following is a brief description of the steps that I took to complete this project. Beginning in section 2, Methods, I explain the procedures and code that I used. I shall explain how I selected the data I used, how I imported my data into Python, and what calculations or procedures I used to create my results. I will also explain how I took those results and generated the plots and comparisons. In section 3, Results, I will go over what those results were, as well as show all of the plots or tables I generated. Finally, in section 4, Conclusion, I will compare my results between supernovae, namely their velocities at the day of maximum brightness, the rate of decline for those velocities, and their colors. For one of the supernova I analyzed, I will compare my results to those of a previous study. I will also discuss any sources of error, the uncertainty of my results, and any other comments or concerns with the results or data.

2. METHODS

Before I began on the project proper, I laid out the work and divided it into roughly three sections. For the first section of the project, I acquired spectral data for several supernovae, then I isolated the Si II absorption line for each spectra, and used this to determine the photospheric velocity of each. After I had collected the photospheric velocities of the supernovae, I then generated several plots based on my data. These plots include: the velocity curves, velocity versus time since day of maximum brightness, and the velocity at the day of maximum brightness against color.

2.1 Data Acquisition and Reading

2.1.1 *Acquiring Data*

For this project, I used the spectra of a total of seven Type Ia supernovae: supernova 2009dc, supernova 2011aa, supernova 2011de, supernova 2011fe, supernova 2012dn, supernova 2016ccj, and supernova 2022hrs, which shall all be hereafter shortened to SN2009dc, SN2011aa, and so forth. The data for each of these supernovae were provided to me by Dr. Peter Brown using the spectra database WiseRep. The first two supernovae for which he provided spectra were SN2011fe and SN2022hrs, both of which were chosen for particular reasons. SN2011fe is relatively old, having been observed over a decade ago, and it was relatively well studied at the time. As a result, there are a multitude of prior papers about it, and I used these to check that my methods and results were reasonable. SN2022hrs, on the other hand, is a much more recent supernova, having only occurred in September of 2022. This supernova was provided to test my code on a relatively new set of spectra. The other five supernovae were provided later on, once the bulk of the finding code was finalized, to ensure that I had enough data for any correlations to be evident.

2.1.2 *Supernovae Colors*

In addition to the supernovae spectrum, Dr. Brown also provided the colors of five of the supernovae: SN2016ccj, SN2012dn, SN2011fe, SN2011aa, and SN2009dc. I used the uvm2-, B-, and V- color bands for this paper. For the B-band and V-band colors, I had the colors and their

error for all five supernovae. However, for SN2009dc, the uvm2-band was not present, so I did not use that supernova in my plot of the uvm2 minus V color.

2.1.3 Determining Day of Maximum Brightness

For the supernovae I used, it was not immediately obvious from the data on what day they reached their maximum brightness based on the spectra alone, so I turned to other sources. For SN2011fe, I used the paper by F. Pata and their co-authors [4]. On page two of this paper, there is a table that has the date relative to the day of maximum brightness. By taking the date and adding the relative time until the day of maximum brightness, I was able to calculate the date. For SN2022hrs, Dr. Brown provided the day of maximum brightness alongside the spectra data. For the other five supernovae, the days of maximum brightness were provided shortly after the spectral data.

2.1.4 Reading In The Data

Before I could begin my analysis and calculations, I began by importing the spectral data for the supernovae into Python in a usable format. For SN2011fe and SN2022hrs, the data was provided in a series of ascii tables of wavelength and flux, and for the other five supernovae, the data was provided in .fits files. For each file type, I began by grouping all of the spectra for each supernovae into their own folder, then I used the os Python script to create a list of file names for each supernovae. For the ascii table files, I used the pandas ".open" function to open the files, and I then used the Spectrum1D function from the specutils library to convert the data into spectrum data. This process resulted in data tables that the other libraries were able to read. For the .fits data, I used the astropy function "fits.open" to open and read the data. When using a .fits file, the data is already calibrated as spectrum data, so I only needed to transfer it into a data table using pandas. Each data table had two columns that being the flux of the supernovae, or how much light is detected on by the telescope broken into discrete wavelength units, and the wavelengths of light detected. These two sets of data together form the spectrum of the supernovae.

2.2 Locating the Si II Feature Wavelength

2.2.1 *Creating the Limited Range*

Once I had the spectrum of supernovae, I set out to isolate the Si II absorption line. Si II has a rest wavelength of 6355\AA , and the photosphere is moving towards the Earth, the absorption line will be shifted to a shorter wavelength. To locate this shifted line, I began by limiting my search to a range of within 200 data points of the rest wavelength. I did so by creating a mask and applying it to my data using the `.iloc` command on top of my flux and wavelength data. On average, this generated a much more manageable range of wavelengths, from approximately 5500\AA to approximately 7200\AA . I further reduced my range by only looking at the points with wavelengths less than the rest wavelength, as that is the direction in which the wavelength will shift for an object approaching the observer. I primarily reduced the range this much for two reasons: calculation time and common sense. The code I used, as described below, locates any and all absorption lines, and having it detect every absorption line over the entire spectral range would cause the code to run far too slowly, especially for the time frame for this project. As for the other consideration, it would not be reasonable for the measured wavelength to be too much of a smaller wavelength, as that would imply that it would be traveling too fast, and if the wavelength were larger than the rest wavelength, that would imply that the photosphere is moving away from Earth, which is not true of the part of the photosphere visible from Earth, because the receding part of the spherically-expanding ejecta is hidden by the dense, optically-thick region below the photosphere.

For the `.fits` data, I also had to smooth my data. When a telescope observes a star, there are small statistical errors and small errors from the light detectors, creating noise. My data for SN2011fe and SN2022hrs appeared to have had their noise reduced, but my data for the other five supernovae were very noisy, which in testing proved to be problematic for future steps. To alleviate this, I performed a procedure referred to as smoothing. To smooth the data, I used two scripts in the `astropy` library: `Gaussian1DKernel` and `convolve`. `Gaussian1DKernel` takes the spectrum data, and breaks it into blocks. `Convolve` takes these blocks, and smooths the results by finding an average value for each block, and smoothing the other points so that it forms a smooth curve. This process

ultimately lessens the effects of the noise on the data, and allows the code to more easily locate the absorption line features present without giving false-positive results.

2.2.2 *Determining the Shifted Velocity*

Once I had reduced the supernovae spectrum range, I located all of the absorption lines contained within the restricted range. To do so, I used a script from the `specutils` library called "absorption_lines," which creates a list of absorption features, their wavelengths, their flux values, and their location number in this new list. To determine the photospheric velocity, I had to first select which of the absorption lines detected represented the Si II absorption line. To do this, I made an assumption: that the change of the wavelength would not be so large as to permit another absorption line to appear in or around the location of the Si II rest wavelength. In the code, this assumption translated into finding the absorption line whose position on the wavelength axis was the closest to the rest wavelength position of 6355\AA . To ensure that my results were good, I then visually confirmed my data by plotting out the restricted range spectrum. For SN2011fe, some of the data the code was unable to locate the correct feature due to line blending. As a result, I eliminated data points such that only six data points remained. For SN2022hrs, none of the data points were particularly poor, so I was able to include nearly all of my data points, with one of them being outside of the time range I imposed, resulting in a total of ten points. For the other five supernovae, earlier on I encountered the issue of the code detecting jaggedness caused by the noise as the absorption line for which I was looking, hence my smoothing the data. I found that, for the code to detect what visually appeared to be the correct wavelength all of the time, I needed the box size for the `Gaussian1DKernel` function to be nine. In terms of data points within twenty days of maximum brightness, SN2009dc had seventeen data points, SN2011aa had eight data points, SN2011de had eight data points, SN2012dn had six data points, and SN2016ccj had three data points.

2.3 **Photospheric Velocity**

Following the determination of the shifted wavelength of the Si II absorption feature, I set out to calculate the photospheric velocity of the supernovae. To do so, I used the Doppler Shift

equation:

$$v = \frac{\lambda_{measured} - \lambda_{rest}}{\lambda_{rest}} \times c \quad (1)$$

Where λ_{rest} is 6355\AA , $\lambda_{measured}$ is the frequency that was determined in the previous step, and c is the speed of light, in meters per second. When the numbers from the previous step were put into this equation, I was able to calculate the photospheric velocity for that instant in time.

One factor that is relevant to the discussions on photospheric velocities is the sign of the numbers calculated from the Doppler Shift. The Doppler Shift equation results in a negative velocity when λ_{rest} is greater than $\lambda_{measured}$. In astronomy, a negative velocity indicates that the object is moving towards the observer, in this case the Earth. For our results, the velocity being negative is expected, since the portion of the photosphere that is observable from Earth is moving towards us. The photospheric velocity is often written as a recessional velocity, meaning positive velocity denotes that the object is moving towards Earth. To adjust for this, I multiplied all of my results by negative one. After I calculated the photospheric velocities and the wavelengths, I proceeded to create my plots and graphs.

2.4 Calculating the Velocity Distribution

When a supernova explodes, not every piece of material ejected during the explosion will be moving with the same velocity. This difference in material velocity causes the wavelength of the light emitted to differ slightly as well. This variance in light wavelength is called the wavelength distribution, which, when multiplied by c/λ_{rest} , the distribution of the velocity of the spectrum can be determined. For my purposes, I remained in the wavelength space to save on computation time, since they ultimately differ only by a scale factor.

It is expected that, in general, the velocity distribution will be normally distributed, so I compared the velocity distribution against a Gaussian, or normal, curve. To plot a normal curve, I needed the mean value of the distribution and its spread. For the mean value, I used $\lambda_{measured}$, since it should be the center of the curve. To determine the spread of the curve, I first needed to calculate the zero point for the curve.

I calculated the zero line in two similar manners. Using `specutils`, I found the emission lines with the `emission_lines` script, and found the lines directly to the left and to the right of the shifted Si II absorption line. For each of these emission lines, I measured their flux. I then created two Gaussian curves; one in which I subtracted the value of the left emission line, and one where I subtracted the value of the right emission line. These subtracted values formed my zero line. To determine the flux for my mean value, I subtracted the zero line value from the flux of the Si II absorption line.

To calculate the spread of the absorption line feature, I used the full width at half maximum of the absorption feature. This is the measure of the width of the curve halfway between the mean value peak and the zero line. I calculated this value by determining the half maximum value, and then creating a horizontal line at this height. This line will intersect the distribution of the velocity curve at two points. I found the points of intersection for the two lines using the `scipy` script `UnivariateSpline`, and then I solved for the difference between the two points, giving me the full width at half maximum. Using this value and the mean, I was able to construct a Gaussian curve and plot it on top of the distribution of the velocity curve. Since I had two emission features, I created a plot for each, the leftward based Gaussian and the rightward based Gaussian. I created a set of curves for the first spectrum in both SN2011fe and SN2022hrs.

2.5 Velocity Decline

I then created the python code to generate and plot the photospheric velocity as a function of the days since maximum brightness. To do so, I began by making a list of the photospheric velocity for each spectrum in a given supernova, and making a second list of the date. I then converted the date into Modified Julian Date (MJD), which is the standard date system used in astronomy and is a measure of the number of days that have occurred since a set zero date. For SN2009dc, SN2011aa, SN2011de, SN2012dn and SN2016ccj, the date for each spectrum was provided in MJD format. For SN2011fe and SN2022hrs, however, the dates were provided as Gregorian dates in the format year, month, day. I converted the dates into MJD using an `astropy` script called `Time`. I repeated this process for the day of maximum brightness as well. For

each spectrum in the supernovae, I then converted the list of MJD dates into days since maximum brightness by subtracting that date in MJD from the time of observation of the spectra. For days before the day of maximum brightness, the date is negative, and for days after the day of maximum brightness, the date is positive. By having the day of maximum brightness be the y-axis intercept, I was to determine the photospheric velocity at the day of maximum brightness by determining the value of the intercept.

I then plotted the photospheric velocities of each supernovae as a function of time. For the velocity axis, I used units of 10^3 kilometer per second, and for the time axis I used units of days since maximum brightness. I chose 10^3 kilometer per second as the units for the velocity axis because that is a standard unit used in astronomy.

To determine the velocity decline gradient, I used two methods, a more simple one that provided the slope of the line and the y-intercept, and a more complex method that also gave the error estimates. The simple method used `poly1D` to plot a best fit line. The more complicated, and more useful, method used the `linmix` Python code library. `Linmix` generates approximately two thousand random lines of best fit, and then determines the line of best fit and the error on the line of best fit. Although `linmix` provides more data, it also requires more data to run. `Linmix` requires several data points to run properly, as well as a margin of error for the time and velocity coordinates for each data point. In my testing, `linmix` will run with six points, albeit with a large error, but any fewer than four points causes `linmix` to crash. As a result, I did not use `linmix` for SN2016ccj and its data, and therefore I do not have proper error estimates for it.

As for my error estimates, I used a different method for SN2011fe and SN2022hrs compared for the others. For those two supernovae, I defined the velocity uncertainty based on the size of the step size between the wavelength values multiplied by a constant. For the time error, I assigned a value of zero point five (0.5) days, since the data only specified the day on which the spectrum was collected. For the other five supernovae, the exact time of observation was provided. I used rather generous error estimates for the velocity and time error, setting both as zero point one (0.1).

I then created a plot of the velocity of the supernovae at maximum brightness against the velocity decline rate of the supernovae. I did not include error bars on this graph because SN2016ccj did not have error bars available, and I did not believe that it was necessary for observing the general trend of the data.

2.6 Color Difference

Finally, I created two velocity versus color plots. For the velocity axes, I used the photospheric velocity at the day of maximum brightness. For the color axes, I looked at two different colors: the $uvm2 - V$ color and the $B - V$ color. The $uvm2$ band is one of the ultraviolet bands on the Swift telescope, B is the blue color band, and V is the visual color band, which roughly corresponds to the colors of light that a human can see. I took the difference between each of these values for a given supernova to determine both of the colors. I also included error bars on this graph. For the colors, the errors for each band were provided, so to determine the total error I added the errors in quadrature. For the velocity axis errors, I used the intercept error calculated by `linmix` for all of the supernovae except SN2016ccj. I estimated the error of this supernova based on the distance between two of its points with very similar MJD dates.

3. RESULTS

Once I obtained the results, I began to analyze the data. My results can be divided into two broad categories: plotting of my data, and the analysis of these plots and how different supernovae compare to each other. I shall thus divide this section in a roughly analogous manner. First, I go over the Velocity Distribution results and graphs. I then display and discuss the individual and composite plots of photospheric velocity against days since maximum brightness. Third, I go over the velocity at maximum brightness and color plots, and their results. Fourth, I compare and discuss any overall trends in the supernovae, and I discuss any comparisons I made between my results and those of previous researchers. Finally, I close the Results section with a discussion of my errors and uncertainty.

3.1 Velocity Distribution

Below are four examples of the velocity distribution curves for SN2011fe and SN2022hrs. These curves are representative of the general shape of all of the velocity distributions of these supernovae regardless of spectrum. SN2011fe appears to be the more normally distributed of the two, with the rightward based Gaussian nearly overlapping the curve in some places, as shown in **Figure 2**. This indicates that the photospheric velocities of SN2011fe are essentially normal. SN2022hrs, on the other hand, is an entirely different situation. Both the leftward and rightward based Gaussian curves greatly underestimate the flux values everywhere but the mean value. The leftward based Gaussian curve also appears to be fairly far to the right of the curve. This indicates that there is more material moving with a velocity higher than the mean.

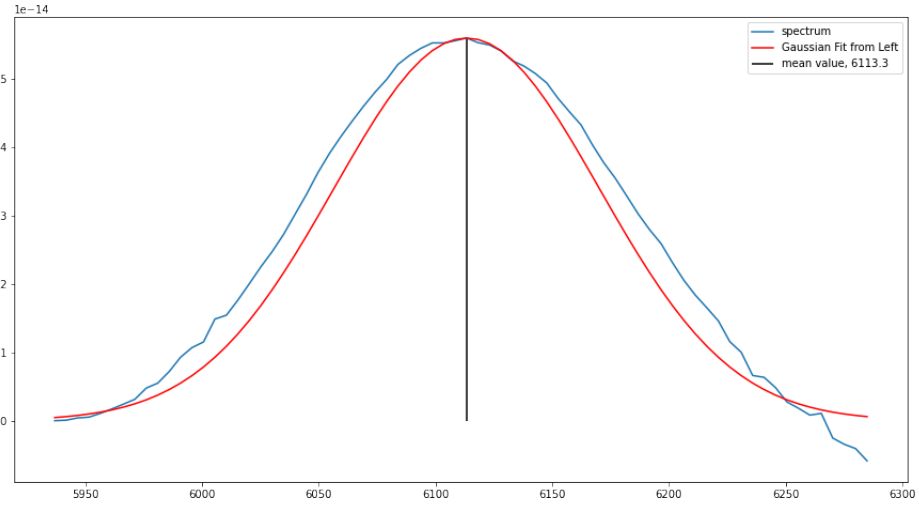


Figure 1: The velocity distribution form one of the spectrum in SN2011fe compared to a left-based Gaussian.

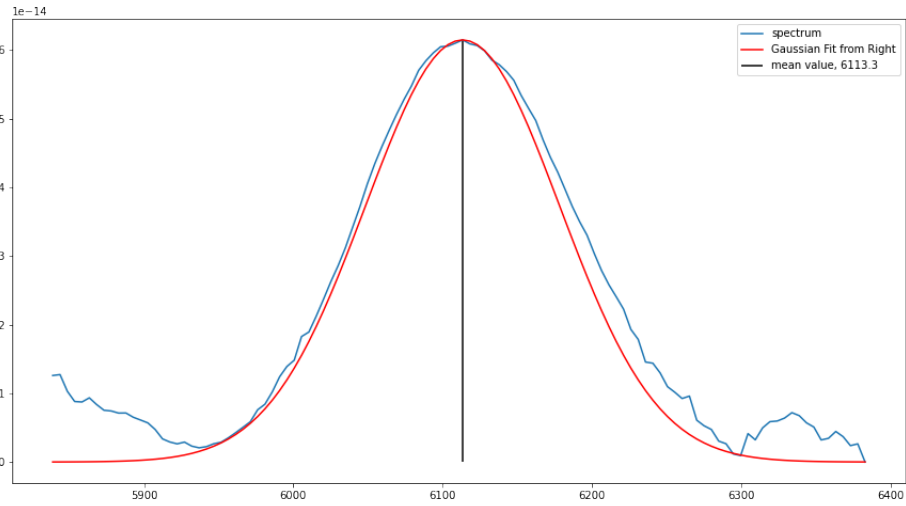


Figure 2: The velocity distribution form one of the spectrum in SN2011fe compared to a right-based Gaussian.

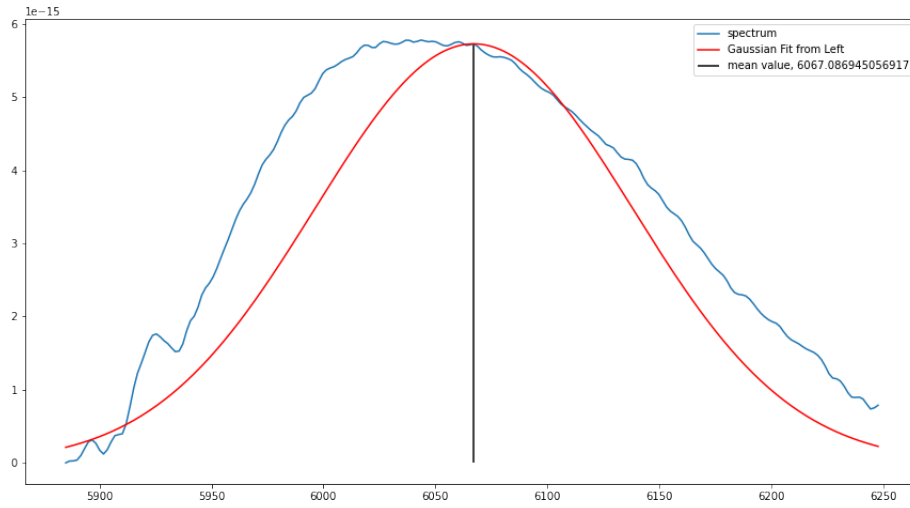


Figure 3: The velocity distribution form one of the spectrum in SN2022hrs compared to a left-based Gaussian.

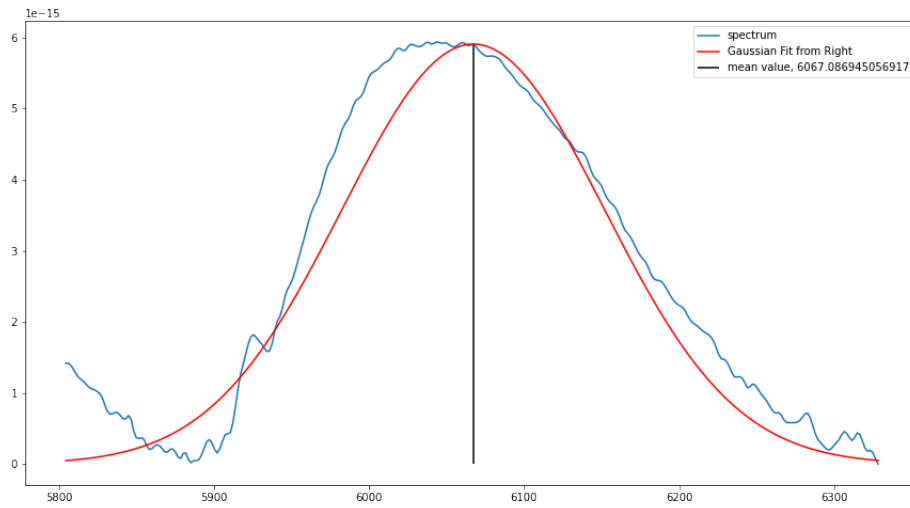


Figure 4: The velocity distribution form one of the spectrum in SN2022hrs compared to a right-based Gaussian.

3.2 Photospheric Velocities

The following plots are of the photospheric velocities against the times since maximum brightness. The dotted black and white line located in the center of the graphs represents the line of best fit for each spectrum. With the exception of the graph for SN2016ccj, the red lines represents possible best fit lines generated by linmix. The blue dots with lines coming out of them are the individual spectrum data points for each supernovae.

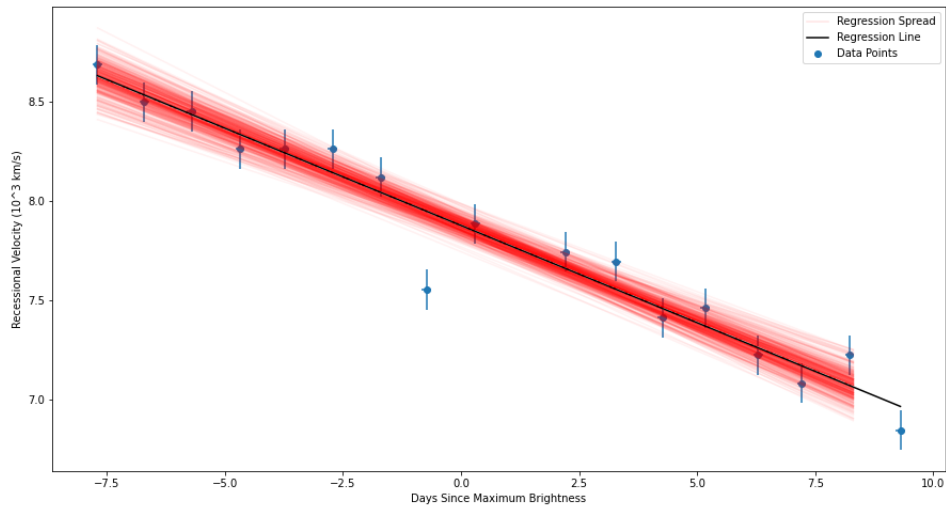


Figure 5: Plot of the photospheric velocity of SN 2009dc over time.

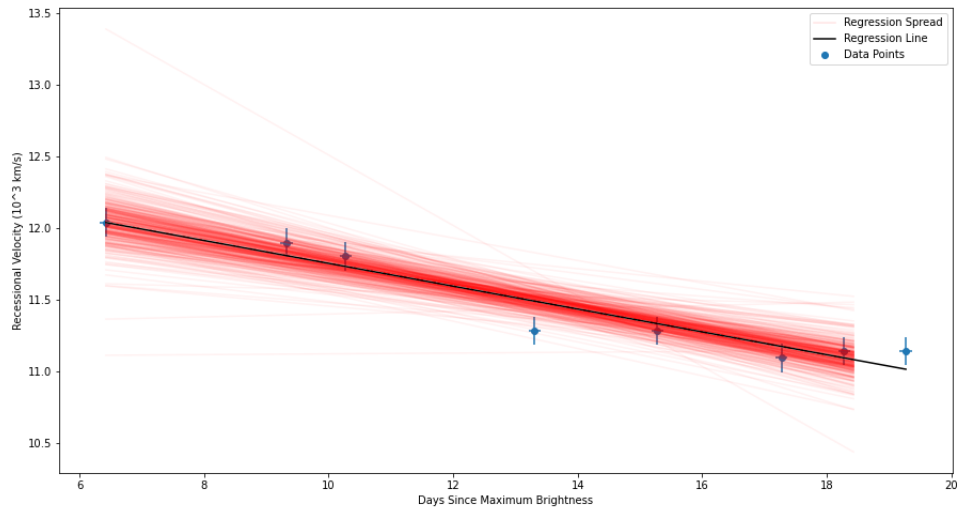


Figure 6: Plot of the photospheric velocity of SN 2011aa over time.

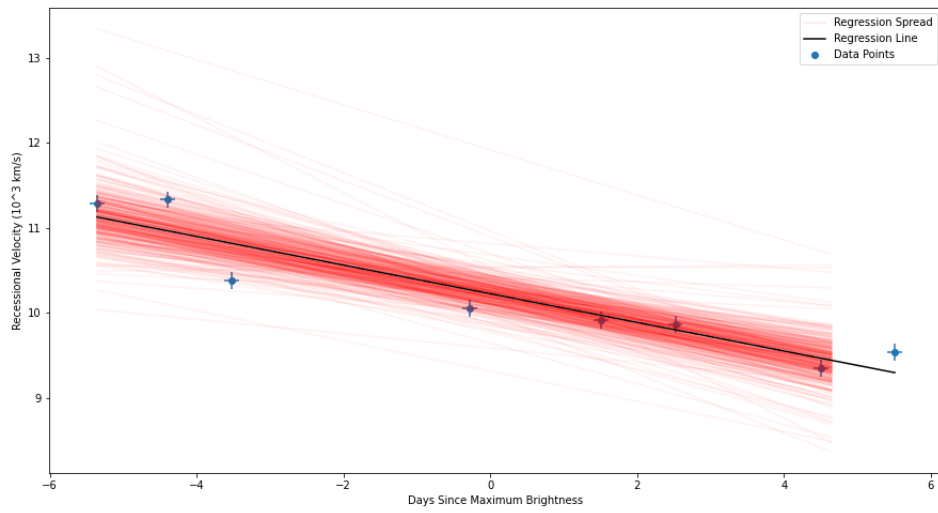


Figure 7: Plot of the photospheric velocity of SN 2011de over time.

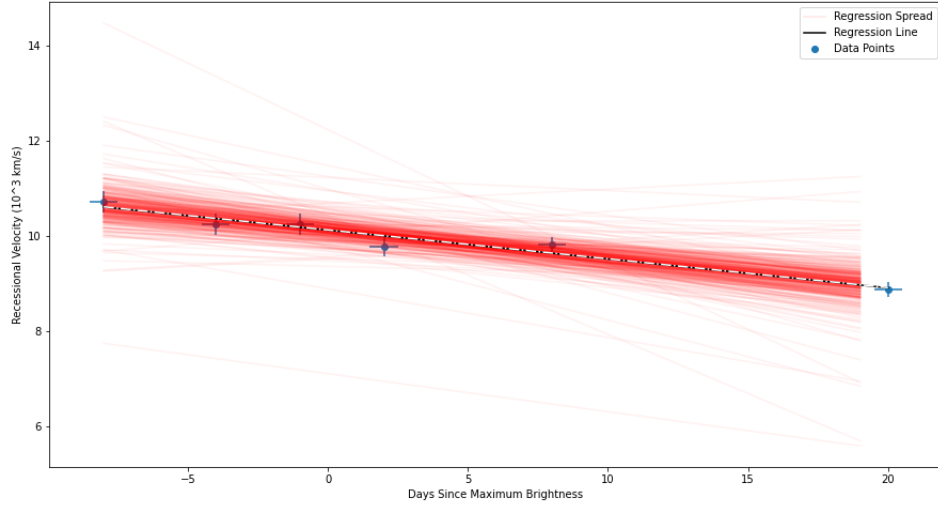


Figure 8: Plot of the photospheric velocity of SN 2011fe over time.

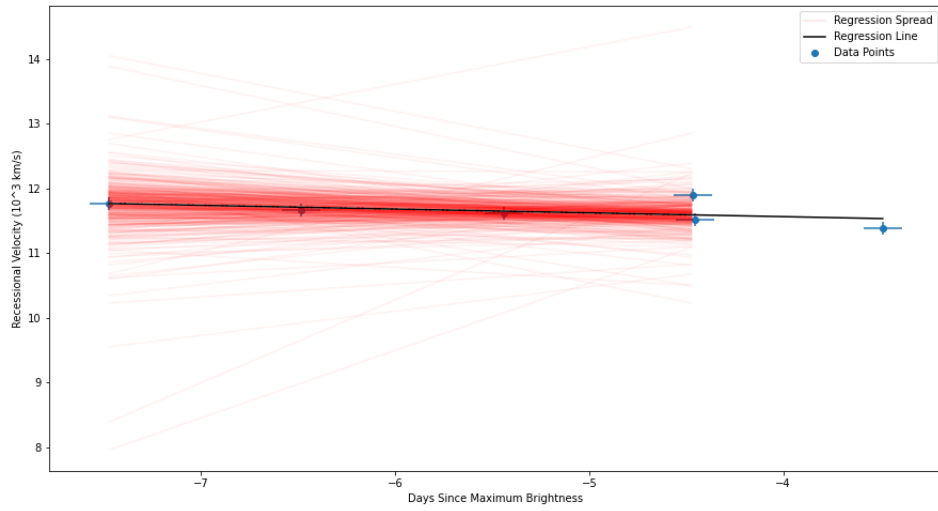


Figure 9: Plot of the photospheric velocity of SN 2012dn over time.

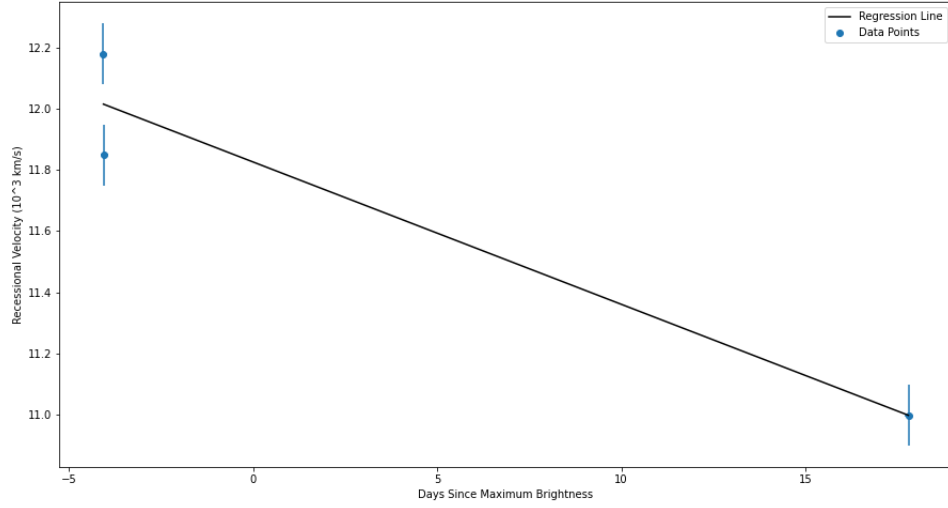


Figure 10: Plot of the photospheric velocity of SN 2016ccj over time.

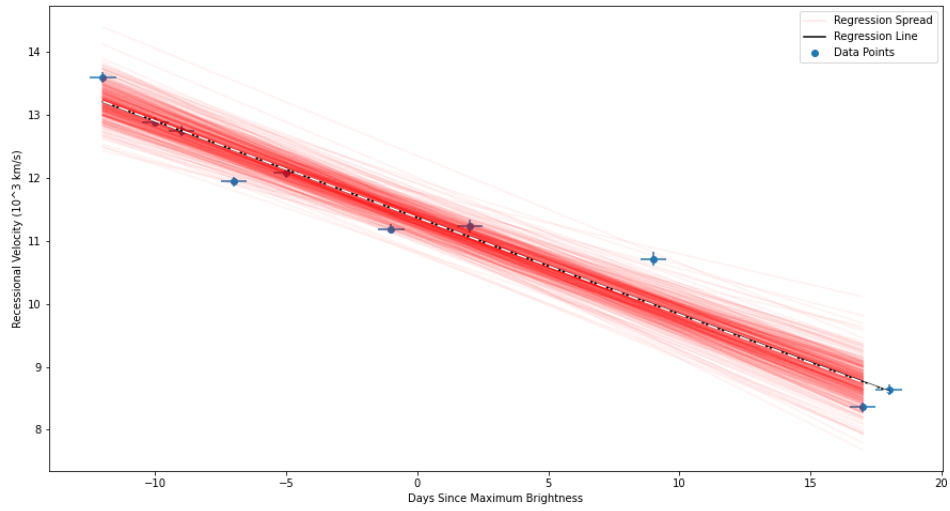


Figure 11: Plot of the photospheric velocity of SN 2022hrs over time.

All of the supernovae investigated in this paper have negative photospheric velocity gradients, indicating that the supernovae slow down over the course of the explosion. This is a reasonable result because the supernovae is losing energy during the explosion.

3.3 Colors

I created two color plots for this data set. The first is the $uvm2-V$ plot, and the second is the $B-V$ color plot. Both are plotted against the photospheric velocity of the supernova at the day of maximum brightness.

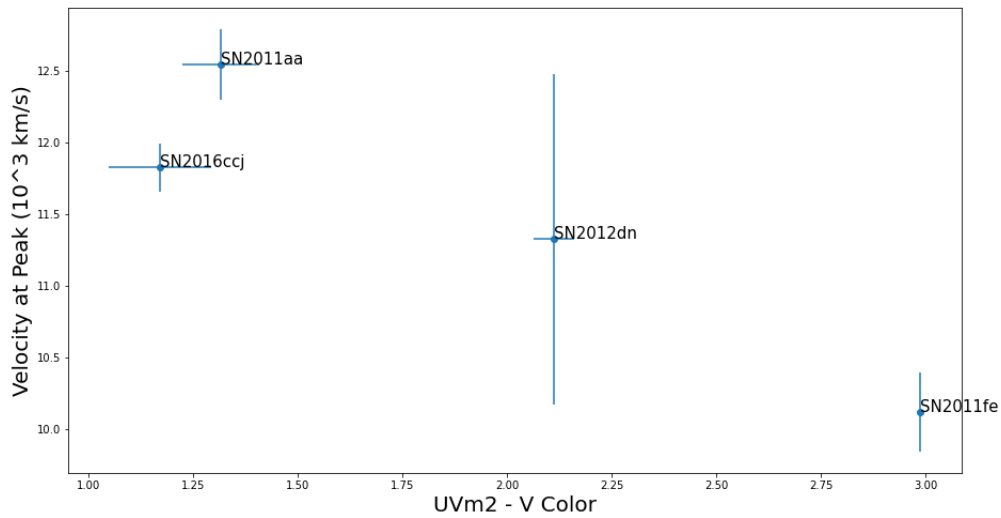


Figure 12: Plot of the photospheric velocities for the supernovae against the $uvm2-V$ color.

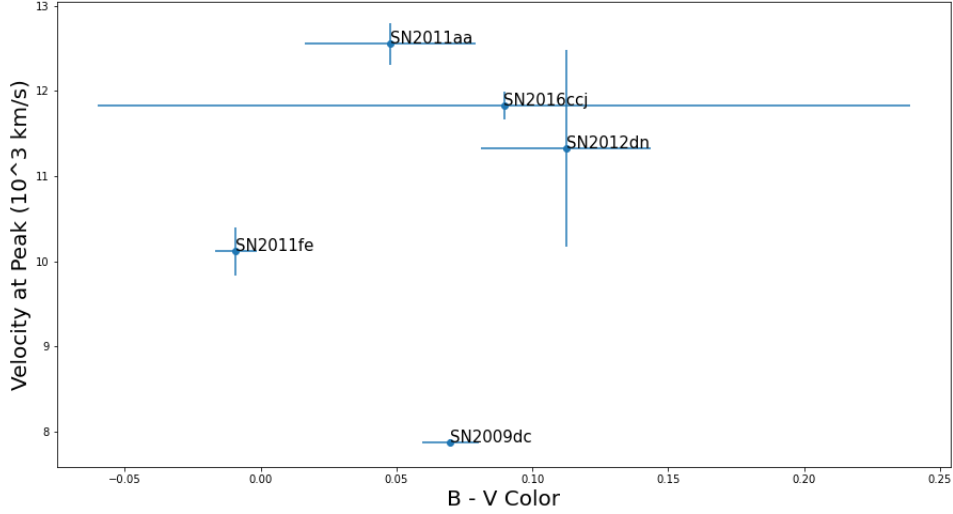


Figure 13: Plot of the photospheric velocities for the supernovae against the $B-V$ color.

Both of these plots show a slight indication that as the color increases, the photospheric velocity at peak brightness decreases. In other words, supernovae that emit less light in the V band compared to either the UVm2 or B bands tend to have slower photospheric velocities than those that emitted more light in the V band than in the other two bands, although the correlation is very weak.

3.4 Comparing Results Across Supernovae

My results for the supernovae are as follows, to three decimal places: SN2009dc has a decline rate of $-0.0980 \cdot 10^3 \frac{km}{s} / day$ and a peak velocity of $7.876 \cdot 10^3 \frac{km}{s}$, SN20011aa has a decline rate of $-0.080 \cdot 10^3 \frac{km}{s} / day$ and a peak velocity of $12.549 \cdot 10^3 \frac{km}{s}$, SN20011de has a decline rate of $-0.168 \cdot 10^3 \frac{km}{s} / day$ and a peak velocity of $10.225 \cdot 10^3 \frac{km}{s}$, SN2011fe has a decline rate of $-0.061 \cdot 10^3 \frac{km}{s} / day$ and a peak velocity of $10.117 \cdot 10^3 \frac{km}{s}$, SN2012dn has a decline rate of $-0.059 \cdot 10^3 \frac{km}{s} / day$ and a peak velocity of $11.326 \cdot 10^3 \frac{km}{s}$, SN2016ccj has a decline rate of $-0.046 \cdot 10^3 \frac{km}{s} / day$ and a peak velocity of $11.826 \cdot 10^3 \frac{km}{s}$, and SN2022hrs has a decline rate of $-0.153 \cdot 10^3 \frac{km}{s} / day$ and a peak velocity of $11.370 \cdot 10^3 \frac{km}{s}$. These results are collected in the plot below.

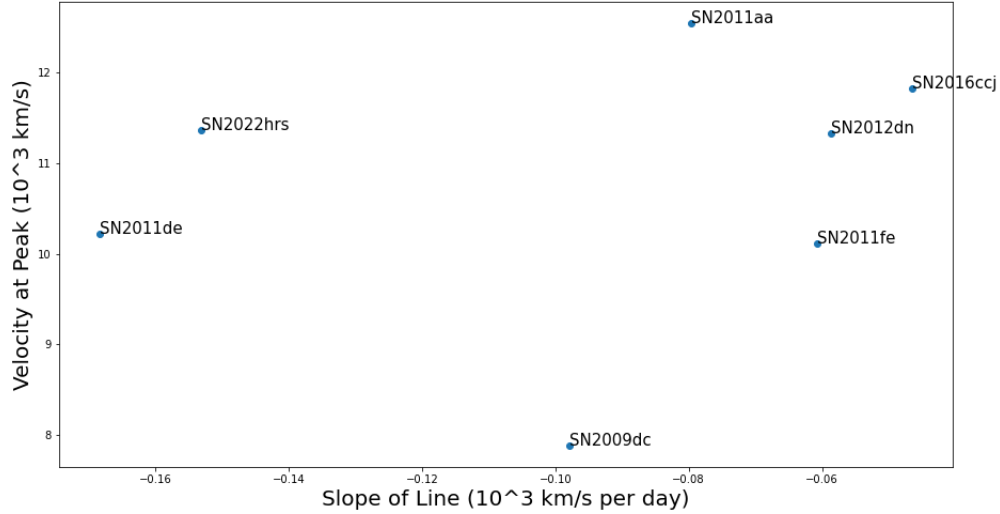


Figure 14: Plot of the photospheric velocities at maximum brightness against the decline gradients.

This graph collects my data on the photospheric velocities of the supernovae and their slopes and compares them to each other. The Velocity at Peak is the photospheric velocity at the day of maximum brightness, and the slope is how quickly the supernova loses its photospheric velocity as a function of time. Generally speaking, there appears to be some weak positive correlation between the velocity at peak and the decline rate. At higher velocities, the decline rate tends to be smaller.

The photospheric velocity of a supernova is related to the energy of the supernova. A more energetic supernova will have more excited material, which will cause the material to have a greater photospheric velocity. The above graph indicates that the more energy a supernova has, the less quickly the supernova loses that energy. The data of more supernovae would need to be calculated for the results to be conclusive.

I also compared my results for SN2011fe against those found in the 2013 paper by R. Pereira and their collaborators [5]. On page 12 of their paper, they also have a graph of the recessional velocity of SN 2011fe. They calculated that the photospheric velocity decline rate of

SN2011fe is approximately $-59.6 \pm 3.2 \frac{km}{s}/day$. When the units are converted, my results lie just within the higher range of their error estimate. This indicates that my results are relatively accurate. I believe that the difference is likely caused by the number of spectra available. Their plot has over twice as many data points as mine, which may pull the slope downward.

3.5 Error and Uncertainty

The final topic is the error and uncertainty of my data. With the exception of SN2016ccj, all of my errors are small in comparison to their respective values. For the slope of the decline, the errors range from around seven percent to around fifty percent. This higher error corresponds to SN2011fe, which had fewer data points than the other supernovae. The error on the photospheric velocity at maximum brightness is also very small, being less than five percent for my data. This indicates that the velocities at peak are highly accurate and the slopes are somewhat accurate.

I did not include the errors on SN2016ccj in the above paragraph because I could not determine them accurately. Linmix seems to require a minimum number of data points to run, and three data points is too few. As a result, I was unable to calculate the error on SN2016ccj.

There is also the consideration of how I assigned uncertainties. For SN2011fe and SN2022hrs, I assigned the time axis an error of one half a day, and for the others I assigned an error of one tenth of a day. Both of these are likely overestimates, which would cause the above errors to be larger than necessary. For the wavelength axis, SN2011fe and SN2022hrs had their errors assigned based on the average difference between data points, whereas for the others I assigned them an error of 0.1. The method used for SN2011fe and SN2022hrs is more accurate, but I was unable to create a similar script for the .fits files. This could also lead the errors on those five to be larger than necessary.

As for actual errors, I believe that there are two possible sources. First, the data itself. Most of the supernovae that I analyzed had less than ten data points. The relatively low numbers of data points caused the errors to be somewhat large, and depending on how they were chosen, they could lead the slope to be higher or lower than it actually is. Second, there is the code that finds the Si II absorption feature. From looking at plots of where it locates the absorption line, it seems to do

a fairly accurate job, although it is not perfect. When working with noisy data, the code had a tendency to think that the noise was a peak and choose the noise false peak, which is why I had to smooth the data. But the smoothing itself could have shifted the peak slightly, which could cause small errors. For SN2022hrs, the data did not have much noise, but the absorption peaks were very broad. It appears that the code would often choose a point slightly to the right in this situation. This could cause the velocity estimate to be slightly higher than it actually was.

4. CONCLUSION

I created a Python script to analyze the spectra of Type Ia supernovae to determine their photospheric velocity and decline rates. Based on the data available, my code seems to function properly, and correlate with that found by other researchers. Based on the results, the photosphere traveled in the direction of the Earth, and this Earthward velocity decreased as a function of time. The velocities appear to be roughly normally distributed. When comparing the results between different supernovae, there appears to be a correlation between the photospheric velocity at the date of maximum brightness and the gradient of the decline rate of the photospheric velocity over time. There also appears to be a correlation between the photospheric velocity at maximum brightness and the color of the supernovae. Analysis of more supernovae is required to determine the strength of these associations.

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