Photometric Observations of Supernovae in BVR and I Filters

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ABSTRACT

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This thesis will cover the research behind the recent supernovae SN 2010hh, 2011dh, 2011fe and 2012aw. The different types of supernovae will be introduced and discussed. The data gathering and processing will be described. The light curve resulting from Type IIb supernova 2011dh will be compared to the template.The light curve for Type II-P supernova 2012aw will be discussed. Finally, the Type Ia supernovae 2010hh and 2011fe will be used to calculate their distance modulus and thus the distance to their respective galaxies NGC 6524 and M101.

Keywords: supernova, Type Ia

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Chapter 1

Introduction

This thesis will introduce the uses of photometry on supernovae. Photometry means that light coming from a source is sent through a color filter so only that color goes through. This allows one to determine properties of the source. In this case, several supernovae events were observed using photometry.

First, several different types of supernova will be described. Then the data gathering and processing techniques will be mentioned. Finally I will mention the results from the data. The results include the photometric data used to create light curves. This data will then be used to analyze the supernova's properties such as the distance modulus and B-V temperature curves.

1.1 Overview

Several different types of supernovae will be briefly introduced. The Type Ia supernovae will be discussed in greater detail than the other supernovae due to their possible use in distance measurements as well as the higher frequency of a Type Ia event compared to other types of supernovae. Light curves of data secured from several supernovae will be presented and results from the supernovae will be discussed.

1.2 Background of Supernovae

Supernovae are among the most energetic events observed in the universe. A supernova usually emits light at a rate greater than "100 million times that of the sun" Bethe (1990). The high level of luminosity that a supernova emits makes it very easy to see them even at extragalactic distances.

Supernovae are very bright but also very rare events. Yet, when they do occur it is often near or within a host galaxy Riess et al. (2009). Statistically this is logical because the majority of stars in the universe are contained within galaxies. Knowing that a supernova is located in a galaxy can help us to understand many of the properties of the galaxy. However, the supernova's proximity to its host galaxy is problematic when securing data. This is due to reddening caused by dust. In the cases of supernovae that will be mentioned in this thesis reddening have been shown to have only a negligible effect on the photometric data.

One use of supernovae is that they are used as standard candles. A standard candle is a celestial object that varies in brightness in a predictable manner over time. I can measure the change in luminosity of the standard candle and plot the change of the "light intensity as a function of time" Bethe (1990) which is calledl a light curve. The light curve can be callibrated to predicted light curve templates for that specific kind of standard candle and determine the distance to that object.

It is important to note that there are different types of supernovae. There are the general type I and type II supernovae. A supernova type is determined by whether or not the spectrum contain helium, the shape of the light curve and the progenitor star. Among these types there are also subtypes of supernovae. The subtypes are categorized by whether or not they contain sodium spectral lines. These types and subtypes will be described in more detail in the next two sections.

Among the different types of supernovae Type Ia are the ones which are used as the standard candles Perlmutter (2003). In other words Type Ia supernova have very predictable light curves. This is used to determine the supernova's distance. Afterwords I use the Supernova's proximity to it's host galaxy to estimate the distance between the milky way and the galaxy which hosts the supernova.

1.2.1 Type l Supernovae

Type I supernovae are defined by having "no hydrogen features in their spectra" Perlmutter (2003). Although, Type I supernovae have this feature, not all Type I supernovae result from the same conditions. Type I supernovae are split into three main subtypes: Type Ia, type Ib, and type Ic. Each subtype of supernova has its own spectral features and light curve behaviors which result from different intial conditions right before the supernova event.

Type Ia supernovae are defined by the strong silicon lines that are found in their spectra Bethe (1990). While the origins of Type Ia supernovae have not been observed directly, there are working models which suggest that they originate in a binary star system containing at least white dwarf. The supernova is thought to be a result from a thermonuclear explosion of the white dwarf star Freedman et al. (2011). While white dwarfs generally do not have thermonuclear reactions they can if “they are in a close, semidetached binary system..." Freedman et al. (2011). The silicon which was mentioned is a remnant of the expoding white dwarf.

The most common model for a Type Ia consists of a giant of supergiant star close enough to a companion white dwarf that it “dumps" gas from its outer atmosphere, mostly hydrogen and helium, to the neighboring white dwarf Freedman et al. (2011). The other common model contains two white dwarfs in the same system Pakmor et al. (2010).

Type Ib and Ic are similar in that their spectra do not contain silicon. They are core-collapse supernovae Freedman et al. (2011). These explosions occur when a large main sequence star reaches the end of its life and explodes Freedman et al. (2011).

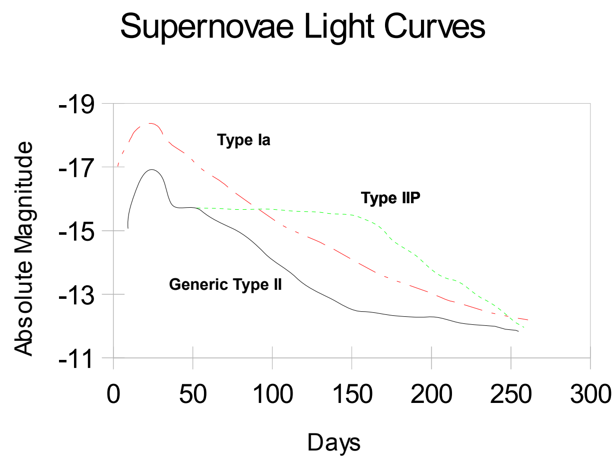

Figure 1.1 A Type Ia supernova quickly reaches its maximum brighness which is followed by a gradual decline. A Type II supernova reach a maxmum, then it declines in “steps" of varying speeds of declination. Type IIP plateau supernovae usually plateaus sometime after the maximum. The plateau typically remains for about 100 days before it begins a slow decline in brightness.

1.2.2 Type ll Supernovae

Type II are similar to type Ib and Ic supernovae due to the fact that they are also core collapse supernovae Freedman et al. (2011). There are several subtypes of type II supernovae, however type IIP supernovae will be the one mentioned in the greatest detail.

Type II supernovae result from the end of the life cycle of a large star of over 9 solar masses. The supernova event occurs when the core goes over the Chandrasekhar limit of 1.4 solar masses and overcomes the electron degeneracy pressure, causing the star rapid collapse. The collapsing atmosphere then rebounds off the rigid neutron core causing the supernova.

Typical type II supernovae have a light curve that consists of an increase in brightness a maximum, a secondary “step" and finally, a slow decline in magnitude Freedman et al. (2011).

There is a special supernova that plateaus at the secondary “step". Figure 1.1 demonstrates the general behavior of the types Ia, IIP and the generic Type II supernovae light curves.

Chapter 2

Introduction to Image Collecting and Processing

There are several problems when using data from a ground based telescope. Some forms of atmospheric interference include turbulence, cloud coverage and light pollution as shown on figure. The ways to deal with these problems will be discussed in section 2.1

Afterward, I will mention possible ways to reduce if not eliminate these atmospheric disturbances. In the second section I will discuss the technological issues that arise from the Charge-Coupled Device (CCD), filters, and mirrors. I will also discuss the process used in order to deal with these technological imperfections in section 2.2.

2.1 Image Collecting for Supernovae

The data was secured at West Mountain Observatory. The telescope used was a 36 inch telescope that had a Finger Lakes PL-09000 CCD camera attached which was used to collect the photons. The size of the view is 3065 x 3065 pixel array in with a seeing of 1 arcsecond per pixel on photometric nights.

The observations were taken from late August to early October in 2010. In total there were thirty-six nights of data taken. Twenty-six of those nights were secured using the B filter.These images were secured throughout whole period of observation. There thirty-one nights of data taken in the V filter which were also taken over the whole period of observations. Finally, fifteen days of images were collected through the R filter. Most of the observations through the R filter were taken in the first month of observations. The images were taken in the blue (B) filter were exposed over a period of 500 seconds per image. Data secured through the B filter usually resulted in 1-2 images during the nigh. The images through the visible (V) and Red (R) filters were exposed over a period of 300 seconds per image. Noting that the exposure time for the V and R filters is much shorter than the exposure time for the B filter so usually 2-3 images were secured per night through those filters.

Bias and dark frames were secured for each night of observations. Flat field frames were also secured when weather permitted. The bias, dark and flat frames were used later when the images were processed. The image processing will be described in Section 2.2.

2.2 Calibrating and Processing Data

Telescope technology is not perfect. Telescopes are built to collect as many photons as possible; however, there are many sources for photons just by working the telescope. If these excess photons are not accounted for, it could cause difficulties when using the images for scientific purposes. Equipment that cause problems include the CCD camera, filters and mirrors. Fortunately, there are also ways of dealing with the technological limitations. Astronomers have image processing techniques in order to deal with these problems.

In order to set a zero point a series of images called bias (or zero) frames are taken. These are taken by closing the shutter and exposing the CCD for "zero" seconds. This allows me to set the zero point for all of the images that are taken that night as long as the CCD remains at the same temperature throughout the night.

Astronomers also have to deal with noise caused by thermal electrons that is accumulated over long exposure times. In order to remove this noise, astronomers use a technique called dark frame subtraction, which allows them to remove the majority of excess noise from an object frame. Dark frame subtraction begins by exposing the CCD camera over a long period of time while the shutter remains closed. The exposure times of the dark frames are close or equal to the exposure time that you intend to use for your observations that night.

The pixels on each CCD camera also vary in sensitivity. In order to take this into account special images called “flats" are taken to measure the comparative sensitivity of the individual pixels. The basic concept is to take an image where the light coming through the telescopes is uniform. There are several techniques that can be used in order to create uniform light distributions; however, flats taken for these data are sky flats taken at either twilight or dawn in a part of the sky where the light is relatively uniform. In order to improve the uniformity of the combined flat images, the telescope is moved by small amounts between each image. Therefore, any outliers can be removed when taking the mean of the images.

Chapter 3

Results

Overall, the light-curve for SN 2010hh has revealed several things. I will able to determine the B-V curve. I can then compare my results with previous supernovae results. Finally I can use the light curve information to determine the distance to the host galaxies NGC 6524 and M101.

3.1 Type Ia Supernovae Light Curves

The light curve also shows that this supernova is a rapid decliner. A rapid decliner is a peculiar Type Ia supernova whose light curve decreases in magnitude faster than usual. The way to determine rapid decliners from regular Ia SNe is by measuring the change in magnitude between the maximum magnitude and the magnitude 15 days after the maximum.

3.2 Core Collapse Supernovae Light Curves

Figure 3.3 is the classic light curve that you would get from the explosion of a star that is more than 8 times the size of the sun. There is a sharp drop-off rate soon after the maximum. However, this drop-off rate flattens out over time. While the change in drop-off rate is not as prominent as shown

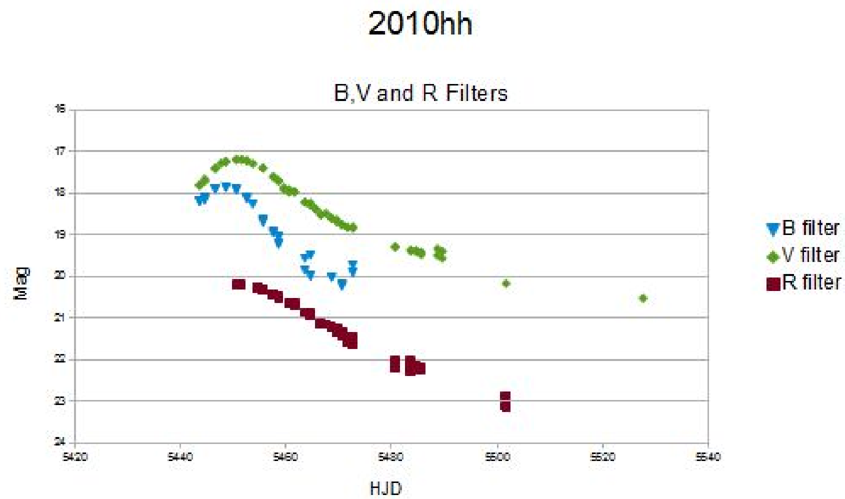

Figure 3.1 B, V and R light curves for type Ia supernova 2010hh.

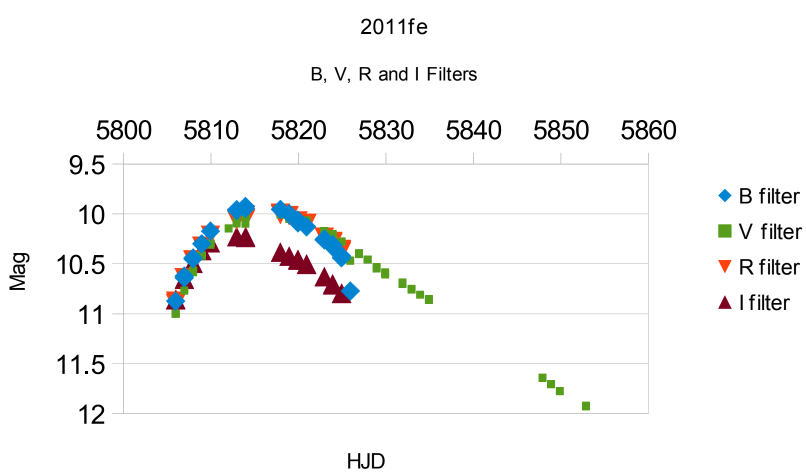

Figure 3.2 B, V, R and I light curves for type Ia supernova 2011fe located in M101.

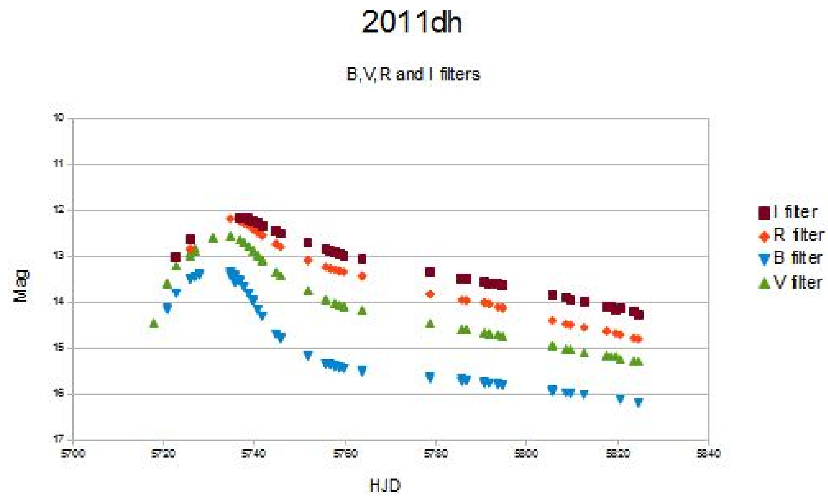

Figure 3.3 B, V, R and I light curves for type IIb supernova 2011dh located in M51.

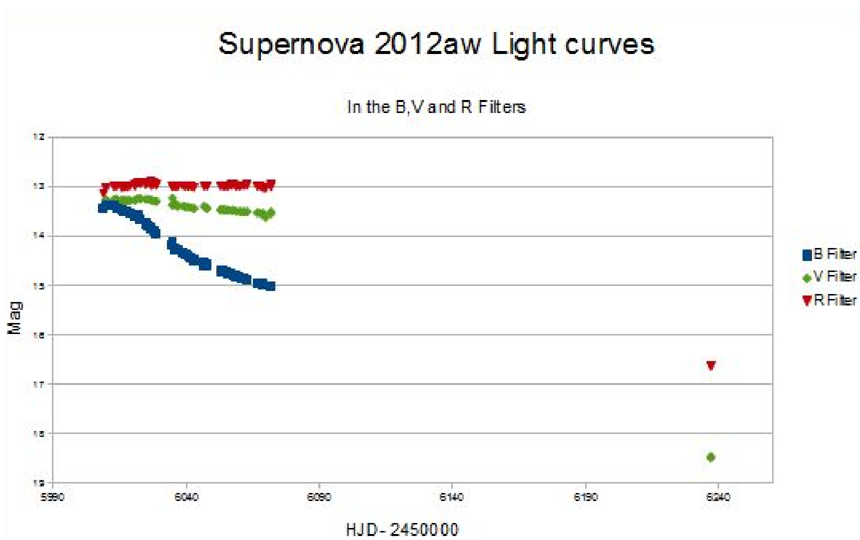

Figure 3.4 B, V and R light curves for type IIP supernova 2011aw.

in Figure 1.1 , there is the definite change in drop-off rate over time for 2010dh that is generally seen in type IIb light curves. Overall, the light curve shows the same type of behavior that has been observed in other Type IIb light curves.

A supernova such as the one in Figure 3.4 is named after the behavior of its light curve in the Red and Infared wavelengths. The type II-Plateau has the distinctive property where the red light stays at a relatively constant magnitude for about 100 days before it begins to die down. This is due to the hydrogen in the outer atmosphere being ionized and decreasing the star's opacity. This makes the supernova emit stronger red light but also block the blue light that otherwise would have been emitted by the star. Unlike other Type II-P supernovae this supernova shows the light curve plateuring right after the star reaches its maximum peak quickly. The analysis of this peculiar behavior will be given in Section 3.3.

3.3 Analysis of Type II Supernovae

Supernova 2011dh proved to be a fairly typical core collapse IIb supernova. The light curve showed the typical “step" decline that occurs due to variable decline rates.

Supernova 2012aw proved to be an unusual plateau supernova. It is more common for a II-Plateau supernova to reach its peak, make a short decline and then plateau for about 100 days. This supernova plateaued right as the supernova reached its peak. This is most likely due to having excessive hydrogen in the stars atmosphere or having a nearby cloud of hydrogen that was ignited by the supernova explosion.

3.4 Using Type Ia Supernovae For Distance Measurements

The distance to celestial objects can be calculated using the distance modulus.

The specific physical limits imposed by the Chandrasekhar limit require that Type Ia supernovae have a similar absolute magnitude at its peak magniude. The absolute magnitude for the B filter is calculated to be -19.6 with an error of 0.2 as determined by Branch & Tammann (1992).

Then using the distance modulus m-M = 5 Log(d)-5 where m is the apparent magnitude at maximum brightness. Solving for d (parsecs) the distance would be

$$\begin{aligned} d &= 10^{(m-(-19.6)+5)/5} \\ &= 10^{(m+24.6)/5} \end{aligned} \tag{3.1}$$

Using distance modulus formula introduced in the last slide I can solve for the distances to these supernovae and their host galaxies.

The distance modulus for NGC 6524 which is the host galaxy for 2010hh is $m - M = 17.8 - (-19.6) = 37.4$.The distance to NGC 6524 can be calculated as

$$\begin{aligned} d &= 10^{(37.4+5)/5} \\ &= 3.02x10^{8}\ parsecs \\ &= 9.84x10^{8}\ ly \end{aligned} \tag{3.2}$$

Similarly, the distance modulus of M101, which was the host galaxy, of supernova 2011fe is $m - M = 9.9 + 19.6 = 29.5$. The apparent peak magnitude of 9.9 has been confirmed by other sources including Munari et al. (2013). There was also very little reddening due to the host galaxy, Pereira et al. (2013) which makes this supernova an ideal test subject.

$$\begin{aligned} d &= 10^{(9.9+24.6)/5} \\ &= 7.94x10^{6}\ parsecs \\ &= 2.59x10^{7}\ ly \end{aligned} \tag{3.3}$$

Some of the calculated distance moduli for M101 are 29.40 ± 0.16 Jurcevic et al. (2000) and 29.05 $\pm$0.14 Stetson et al. (1998), and more were calculated using Cepheids located in M101.This gives an error of 0.3% for the distance calculated from 2011fe.

Figures 3.5 and 3.6 show the temperature change of the supernovae over time. It also shows that that light through the B filter will reach its peak before the V filter. The B-V curves were

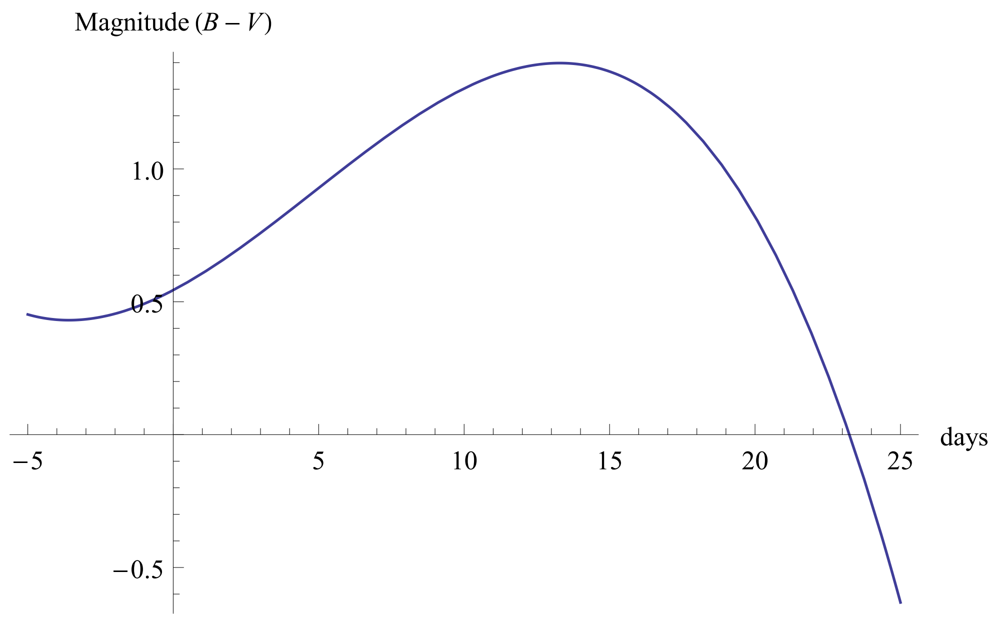

Figure 3.5 B-V temperature curve for 2010hh. Calculated using the polynomial fits for the B and V light curves of 2010hh.

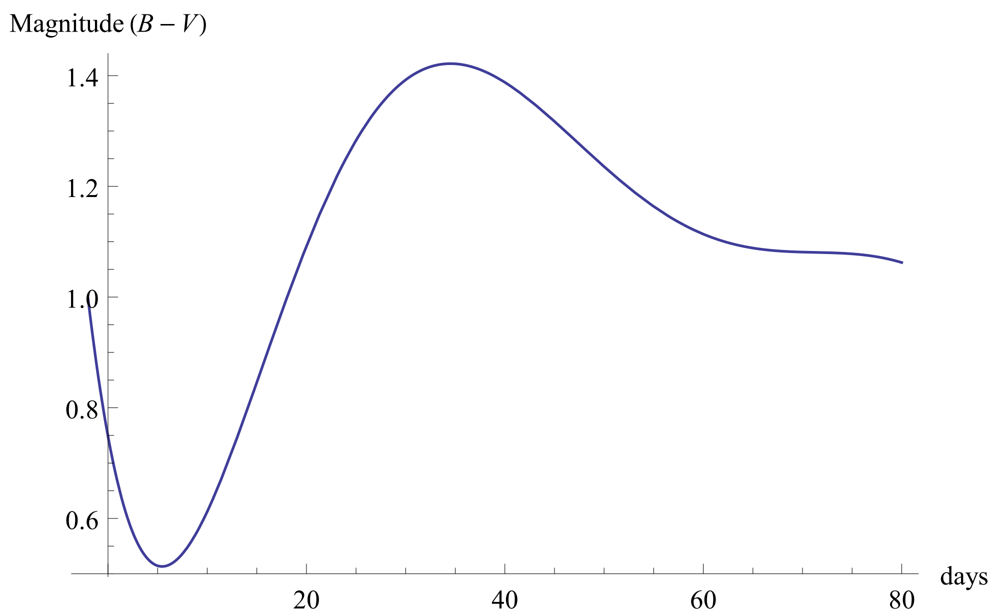

Figure 3.6 B-V temperature curve for 2011dh. Calculated using the polynomial fits for the B and V light curves of 2011dh

determined by doing a least squares fit on a polynomial of the 7th degreee on the B and V light curves. The V fit was then subtracted from the B fit to determine the approximate behaviour of the B-V curves for each of the supernovae.

Using the polynomial fits I was also able to extrapolate the decline parameter Delta $m_{15}(B)$. Delta m_{15} is used to determine the absolute magnitude of a type Ia suepernova using the phillips relationship $M_{max}(B) = -21.726 + 2.698\Delta m_{15}$ from Phillips (1993). My calculated $\Delta m_{15} = 1.15 \pm 0.1$ which correlates with the decline value of $\Delta m_{15} = 1.21 \pm 0.03$ given in Richmond & Smith (2012). This gives us an absolute magnitude, of $M_{max}(B) = -18.75$. This results in a distance modulus of $9.9 - (-18.54) = 28.65$. Due to the extrapolation of the decline value the error is relatively high which is most likely why the distance modulus calculated by the peak magnitude and the phillips relationship are different by over .1 magnitude.

The phillips relationship for 2010hh is calculated to be $\Delta m_{15}(B) = 1.01\pm$ using the polynomial fit of the light curve in the B filter. The absolute Magnitude would be $M_{max}(B) = -19.00$ Which would give us a distance modulus of 17.8- (-19.00)= - 36.80.

3.5 Conclusion

In conclusion, I have found the distance modulus for NGC 6542 to be approximately 37.4 and the distance modulus for M101 to be 29.5. However the distance modulus found by the phillips relation seems to have value it may be in need of futher callibration so we can get smaller errors when calculating the absolute magnitude of the supernova in question.

We have also taken the B-V temperature curves which gives us an idea of how a supernova's temperature changes over time. It also gives a better view of how and when the maximum occurs in the B filter compared the V filter. With these graphs we can see how the light through the B filter always reaches its peak before the V filter.

The plateau supernova 2012aw went to a plateau as soon as it reached its maximum. This suggests a higher proportion of hydrogen in the progenitor star's atmosphere compared to the usual supernova. It also may be a sign of a nearby hydrogen cloud which would have been energized by the explosion which would give off the same red light that the supernova would.

Overall, the results were fairly consistent with previous research in the area of Supernovae and any inconsistencies can be taken into account due to several possible progenitor conditions.

Appendix A

Supernovae Data

Table A.1 2010hh B Filter Data

HJD	B Mag	Error
5443.693965	18.198	0.050
5444.664477	18.098	0.100
5446.64161	17.897	0.024
5448.678069	17.848	0.032
5450.644749	17.912	0.090
5452.64659	18.094	0.086
5453.748288	18.267	0.217
5455.704887	18.702	0.123
5457.632135	18.948	0.140
5458.630827	19.232	0.168
5463.607008	19.567	0.216
5464.667758	20.000	0.010
5468.672259	20.020	0.086
5470.622562	20.193	0.231
5472.655652	19.731	0.765
5443.701187	18.200	0.018
5444.671699	18.164	0.133
5446.64882	17.897	0.020
5448.682964	17.856	0.032
5450.651971	17.921	0.105
5452.653812	18.132	0.257
5455.712109	18.647	0.140
5457.639346	18.927	0.066
5458.638038	19.059	0.039
5463.61423	19.854	0.183
5464.67498	19.486	0.263

Table A.2 2010hh V Filter Data

HJD	V mag	error
5480.678887	19.292	0.038
5483.651081	19.368	0.018
5484.656569	19.405	0.038
5485.600994	19.482	0.006
5488.690931	19.494	0.037
5489.600856	19.57	0.302
5501.676428	20.174	0.176
5527.573688	20.527	0.841
5472.67079	18.845	0.225
5480.682625	19.295	0.047
5483.654831	19.390	0.005
5484.663791	19.379	0.021
5485.608216	19.422	0.044
5488.698141	19.334	0.033
5489.608066	19.400	0.294
5472.678001	18.812	0.504
5443.707414	17.803	0.069
5444.67759	17.6645	0.124
5446.656806	17.414	0.063
5447.768968	17.287	0.019
5448.671414	17.247	0.026
5450.658163	17.194	0.002
5451.642088	17.198	0.014
5452.660062	17.227	0.086
5455.692295	17.399	0.100
5457.651116	17.600	0.053

Table A.3 2010hh R Filter Data

HJD	R Mag	Error
5450.666288	20.215	0.002
5450.670038	20.210	0.003
5451.633732	20.215	0.001
5451.637482	20.212	0.027
5454.774596	20.266	0.003
5454.779503	20.272	0.024
5455.684506	20.320	0.003
5455.688256	20.327	0.059
5457.660919	20.446	0.009
5457.664669	20.428	0.034
5458.656	20.496	0.014
5458.65975	20.524	0.069
5460.632575	20.662	0.010
5460.636162	20.642	0.017
5461.680929	20.677	0.007
5461.684667	20.663	0.102
5463.62865	20.868	0.0095
5463.6324	20.868	0.006
5464.688683	20.88	0.021
5464.692421	20.921	0.101
5466.644379	21.125	0.014
5467.61659	21.154	0.031
5468.653348	21.217	0.010
5468.657098	21.238	0.017
5469.67109	21.274	0.046
5469.674829	21.366	0.019

Table A.4 2010dh B Filter Data

HJD	B Mag	Error
5720.798958	14.147	0.007
5720.804444	14.161	0.183
5722.756339	13.795	0.007
5722.758341	13.810	0.154
5725.841288	13.501	0.010
5725.846774	13.481	0.008
5725.85226	13.497	0.020
5726.881444	13.457	0.0005
5726.88693	13.456	0.028
5727.888755	13.399	0.004
5727.892609	13.408	0.028
5734.718242	13.352	0.002
5734.720256	13.347	0.029
5734.725487	13.406	0.003
5734.733288	13.413	0.02
5734.741377	13.363	0.014
5734.749166	13.392	0.020
5735.700173	13.433	0.015
5735.701481	13.463	0.050
5735.706515	13.564	0.007
5735.714315	13.579	0.001
5735.722116	13.583	0.011
5736.808299	13.561	0.011
5736.810313	13.537	0.072
5737.704622	13.682	0.002
5737.706636	13.676	0.071

Table A.5 2011dh V Filter Data

HJD	V Mag	Error
5717.794904	14.461	0.004
5717.802705	14.469	0.436
5720.759632	13.597	0.002
5720.765118	13.602	0.003
5720.770603	13.596	0.185
5722.760632	13.225	0.002
5722.762646	13.220	0.106
5725.822817	13.008	0.003
5725.828303	13.002	0.038
5725.833789	12.925	0.049
5726.863899	12.826	0.033
5726.869385	12.894	0.002
5726.87487	12.890	0.013
5730.873016	12.612	0.006
5730.877344	12.599	0.003
5730.880723	12.606	0.006
5730.882737	12.618	0.025
5734.704863	12.568	0.0007
5734.706067	12.566	0.001
5734.714122	12.563	0.001
5734.715673	12.561	0.041
5736.812686	12.644	0.002
5736.8147	12.640	0.036
5737.709575	12.713	0.006
5737.711589	12.699	0.043
5738.73677	12.7855	0.001

Table A.6 2011dh R Filter Data

HJD	R Mag	Error
5725.859782	12.836	0.014
5725.867583	12.865	0.034
5734.698296	12.183	0.0012
5734.69943	12.186	0.017
5736.81676	12.220	0.009
5736.818079	12.238	0.018
5737.715733	12.275	0.003
5737.717052	12.267	0.022
5738.742221	12.312	0.011
5738.743529	12.336	0.039
5739.708771	12.414	0.003
5739.71009	12.407	0.036
5740.719798	12.479	0.001
5740.721117	12.482	0.033
5741.724876	12.549	0.003
5741.726878	12.542	0.096
5744.748364	12.734	0.002
5744.749973	12.740	0.030
5745.771509	12.801	0.083
5745.773049	12.801	0.002
5745.781185	12.805	0.001
5745.783198	12.802	0.138
5751.825138	13.079	0.009
5751.82714	13.098	0.068
5755.740959	13.235	0.001
5755.742973	13.232	0.021

Table A.7 2011dh I Filter Data

HJD	I mag	Error
5722.769185	13.022	0.002
5722.771199	13.018	0.186
5725.886876	12.646	0.244
5736.819653	12.157	0.004
5736.820972	12.166	0.003
5737.718591	12.159	0.003
5737.719911	12.167	0.015
5738.745114	12.198	0.010
5738.746434	12.176	0.038
5739.711757	12.252	0.007
5739.713076	12.237	0.028
5740.723189	12.293	0.002
5740.724508	12.290	0.020
5741.729089	12.332	0.005
5741.731103	12.342	0.054
5744.751755	12.451	0.003
5744.751755	12.457	0.002
5744.75341	12.461	0.027
5745.776937	12.516	0.0007
5745.778939	12.515	0.105
5751.829802	12.725	0.005
5751.831816	12.714	0.065
5755.747093	12.844	0.012
5755.749106	12.869	0.013
5756.734723	12.897	0.0002
5756.736737	12.896	0.008

Table A.8 2011fe B Filter Data

HJD	B Mag	Error
5805.960237	10.873	0.001
5805.961325	10.876	0.127
5806.939832	10.622	0.008
5806.940919	10.639	0.095
5807.949854	10.449	0.004
5807.950942	10.440	0.070
5808.944554	10.298	0.063
5809.941697	10.171	0.0005
5809.946408	10.172	0.108
5812.929033	9.956	0.005
5812.93011	9.966	0.021
5813.929987	9.924	0.010
5813.931886	9.945	0.0045
5817.932886	9.954	0.003
5817.933881	9.960	0.018
5818.917953	9.997	0.013
5818.922397	9.999	0.030
5819.925023	10.061	0.013
5819.929166	10.087	0.019
5820.922348	10.127	0.002
5820.92648	10.122	0.065
5822.941898	10.252	0.003
5822.946042	10.259	0.034
5823.904261	10.328	0.010
5823.908381	10.307	0.065
5824.918754	10.439	0.009

Table A.9 2011fe V Filter Data

HJD	V Mag	Error
5805.962668	11.001	0.002
5805.963756	10.998	0.115
5806.942285	10.767	0.001
5806.943373	10.764	0.099
5807.947598	10.565	0.009
5807.948686	10.584	0.083
5808.945631	10.417	0.054
5809.942785	10.309	0.006
5809.947496	10.296	0.075
5812.003219	10.144	0.002
5812.004307	10.149	0.039
5812.932783	10.070	0.012
5812.933756	10.095	0.031
5813.936434	10.031	0.033
5813.937754	10.098	0.032
5813.952939	10.033	0.006
5813.954374	10.021	0.007
5817.930536	10.006	0.000
5817.931532	10.005	0.010
5818.918983	10.027	0.011
5818.923427	10.050	0.009
5819.926053	10.069	0.008
5819.930196	10.051	0.005
5820.923379	10.062	0.011
5820.92751	10.085	0.043
5822.942928	10.171	0.001

Table A.10 2011fe R Filter Data

HJD	R Mag	Error
5805.965203	10.897	0.011
5805.966291	10.874	0.117
5806.944681	10.638	0.0002
5806.945769	10.638	0.089
5807.944542	10.459	0.002
5807.94563	10.463	0.070
5808.946719	10.323	0.054
5809.943873	10.214	0.002
5809.948584	10.210	0.008
5812.934901	10.044	0.028
5812.935874	10.060	0.025
5813.939756	10.010	0.020
5813.941423	10.051	0.008
5813.950612	10.034	0.014
5817.928268	10.005	0.006
5817.929263	9.991	0.012
5818.919955	10.017	0.003
5818.924399	10.024	0.022
5819.927014	10.070	0.001
5819.931157	10.066	0.0138
5820.924351	10.094	0.003
5820.928483	10.099	0.066
5822.943889	10.231	0.001
5822.948032	10.233	0.021
5823.906252	10.276	0.006
5823.910384	10.289	0.033

Table A.11 2011fe I Filter Data

HJD	I Mag	Error
5805.967506	10.854	0.002
5805.968594	10.860	0.101
5806.947204	10.656	0.003
5806.948292	10.649	0.076
5807.941868	10.495	0.001
5807.942956	10.492	0.063
5808.947807	10.366	0.037
5809.944961	10.290	0.031
5812.937019	10.227	0.0002
5812.937992	10.228	0.003
5813.944304	10.234	0.005
5813.94655	10.227	0.078
5817.92387	10.383	0.0005
5817.924957	10.382	0.019
5818.920985	10.421	0.001
5818.925418	10.419	0.022
5819.928044	10.464	0.004
5819.932187	10.454	0.024
5820.925381	10.503	0.0008
5820.929501	10.504	0.061
5822.944919	10.627	0.036
5822.949062	10.627	0.042
5823.907282	10.711	0.005
5823.911414	10.699	0.048
5824.921775	10.796	0.046
5824.92593	10.793	0.0018

Table A.12 2012aw B Filter Data

HJD	B Mag	Error
6008.899447	13.425	0.001
6008.90072	13.429	0.022
6009.729993	13.384	0.001
6009.731266	13.386	0.0003
6012.786032	13.385	0.0003
6012.787305	13.385	0.021
6013.808485	13.427	0.001
6013.809758	13.429	0.014
6015.759271	13.458	0.002
6015.771551	13.463	0.014
6016.666309	13.492	0.003
6016.667582	13.485	0.000
6016.684075	13.487	0.001
6016.685348	13.490	0.008
6017.656617	13.507	0.004
6017.657196	13.516	0.007
6018.745032	13.530	0.001
6018.746074	13.528	0.03
6020.670482	13.588	0.005
6020.671755	13.598	0.011
6021.668874	13.576	0.014
6021.682172	13.604	0.024
6022.681384	13.653	0.003
6022.682194	13.646	0.048
6024.678046	13.743	0.007
6024.678625	13.728	0.031

Table A.13 2012aw V Filter Data

HJD	V Mag	Error
6008.902769	13.376	0.004
6008.904042	13.367	0.056
6009.73424	13.254	0.007
6009.735513	13.269	0.008
6012.790407	13.252	0.0007
6012.791691	13.253	0.0005
6013.811541	13.252	0.003
6013.812814	13.246	0.010
6015.761193	13.266	0.0057
6015.767489	13.278	0.0017
6016.674538	13.281	0.004
6016.675811	13.289	0.010
6016.681274	13.268	0.005
6016.682547	13.279	0.002
6017.65789	13.2735	0.001
6017.658469	13.276	0.002
6018.747972	13.271	0.004
6018.749013	13.279	0.008
6020.668989	13.263	0.005
6020.673132	13.274	0.021
6021.67017	13.231	0.001
6021.676246	13.233	0.0002
6022.68319	13.233	0.004
6022.684	13.242	0.003
6024.677351	13.249	0.001
6024.679423	13.246	0.001

Table A.14 201fe R Filter Data

HJD	R Mag	Error
6008.905755	13.142	0.0007
6008.907028	13.141	0.058
6009.737886	13.024	0.004
6009.739159	13.014	0.008
6012.795869	12.998	0.0005
6012.797142	12.997	0.008
6013.814237	12.981	0.0005
6013.81551	12.9825	0.015
6015.763067	13.013	0.009
6016.678265	12.995	0.004
6016.679538	12.988	0.006
6017.659464	13.001	0.0002
6017.660043	13.001	0.009
6018.752173	12.982	0.008
6018.753214	12.982	0.007
6020.667519	12.967	0.006
6020.674509	12.980	0.029
6021.673075	12.922	0.0003
6021.673769	12.923	0.004
6022.685122	12.932	0.006
6022.685932	12.919	0.017
6024.676356	12.955	0.002
6024.680106	12.951	0.019
6025.653807	12.911	0.0005
6025.66067	12.912	0.030
6026.722477	12.973	0.036

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