Photometry and Analysis of SN 2013aa Supernova

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Abstract

This project involved analyzing SN 2013aa, a supernova located in NGC 5643, using images taken using the Las Cumbres Observatory Global Telescope Network. The goal of the project was to create a light curve of the SN 2013aa supernova explosion, which was be used to estimate the supernova's distance from Earth. This was done using the python scripting language, making use of scientific libraries like matplotlib, numpy, and pylab to do the mathematical heavy lifting and graphing, as well as existing tools like SExtractor and the StarMatch python file. A secondary goal of the project was to calculate the mass of Nickel-56 synthesized by the supernova explosion, which, by decaying to Iron-56, is the main source of luminosity observed.

1 Introduction, Motivation, and Related Works:

Visible supernovae occur only about once every several years, but seeing the explosion itself is difficult because it lasts a mere ten seconds. Type Ia supernova are some of the easiest to observe and catalog because they all form from the same process. Type Ia supernovae occur when a white dwarf nearly accretes enough material to reach the Chandrasekhar limit of around 1.44 solar masses[1]. When this happens, the white dwarf begins carbon fusion due to the increasing temperature and density inside of its core. The star is then thrown out of hydrostatic equilibrium, as its electron degeneracy pressure is no longer enough to withstand the gravity of the star's plasma[2], causing much of the star's matter to ignite in nuclear fusion, releasing the energy required to cause a supernova explosion. This explosion generates a large shockwave and becomes incredibly bright, peaking at an absolute magnitude of around -19.3[3]. Supernovae are extremely important because their remnants can trigger new star formation by creating molecular clouds of material from which stars form. Scientists can also use these supernova explosions as standard candles in order to better understand the universe[9].

When a white dwarf explodes in a supernova, a large portion of its mass is fused into Nickel-56 isotopes. In the time immediately following the blast, these Nickel-56 molecules begin to radioactively decay into Cobalt-56 isotopes, and then into Iron-56 isotopes. This process releases energy as light and is largely responsible for the incredible brightness that type Ia supernovas produce. There have been many publications concerning this topic in the past, one interesting paper in particular attempted to find the maximum limit of Nickel-56 that could be produced in a type Ia supernova[10]. The amount of Nickel-56 formed in a given supernova is important to know because it gives us slightly more knowledge about our own origins and where the heavier elements that we find on Earth came from. Due to the rarity of supernovae, there is still an abundance of information to discover concerning their birth and evolution. It is incredibly important that we seize every opportunity to study them that we can.

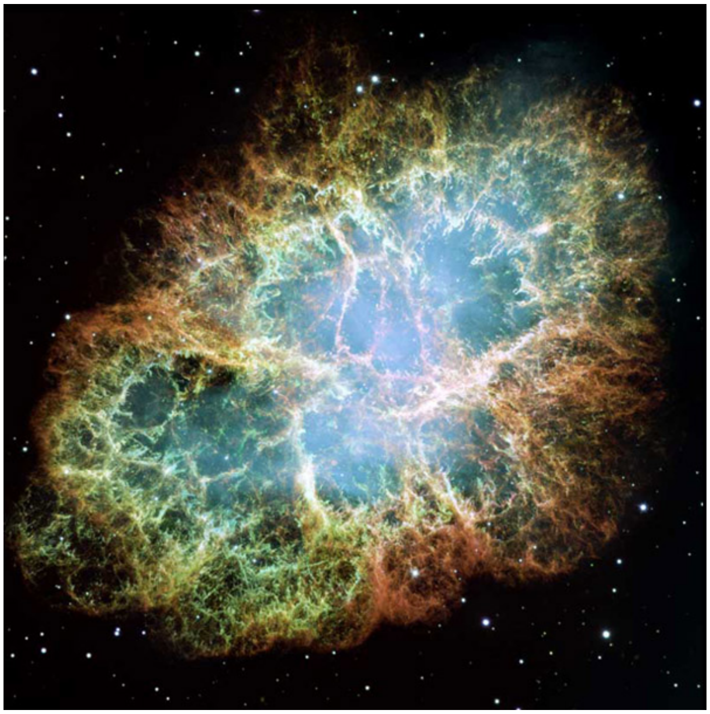

Figure 1: The crab nebula is the remnant of a supernova explosion, and now serves as the birthplace of new stars

This particular supernova, SN 2013aa, was chosen for this project because good, available data existed for it and there had been proven to be a light curve found from the images. SN 2013aa has a right ascention of 14 32 33.88 and a declination of -44 13 27.8 and is located in NGC 5643, a spiral galaxy 16.9 Mpc from Earth[4]. According to the images which discovered the supernova, it had a peak apparent magnitude of 11.7[7].

2 Method:

The method employed to generate the light curve for the supernova is known as photometry, or the science of the measurement of light. I was given images of the supernova taken from between 56300 Modified Julian Date, or MJD, to 56500 MJD, in the FITS format. These images were taken using the Las Cumbres Observatory Global Telescope Network (LCOGT), on a 1 meter telescope located at Cerro Tololo Inter-American Observatory. The camera used was a kb77 ccd with the SDSS g, i, and r filters[5]. The g filter is centered at 4770 Angstroms (Å) with a wavelength width of 1500Å, filtering most non-blue light. The i filter is centered at 7545Å and has a wavelength width of 1290Å, filtering all but red and infrared wavelengths. The r filter is centered at 6215Å with a wavelength width of 3190Å, placing it in the red end of the spectrum as well. In order to calibrate the images to minimize most sources of error, I first chose both a calibration image for each filter, as well as a calibration star for all filters. The chronologically first images taken were the images chosen as calibration images and star TYC 7818-1832-1 was chosen for calibration. The TYC star was chosen because of its short distance from SN 2013aa and because of its known absolute and apparent magnitudes. TYC 7818-1832-1 has a right ascention of 14 32 26.213 and a declination of -44 15 10.50, with a B magnitude of 12.42 and a V magnitude of 11.78[4].

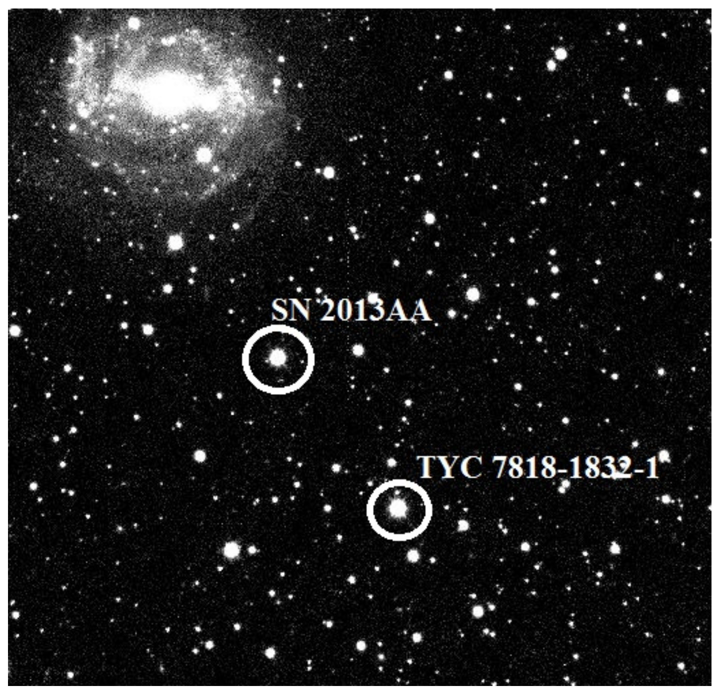

Figure 2: SN 2013aa and calibration star TYC 7818-1832-1, chosen for its proximity to SN 2013aa and its known magnitudes.

In order to find the apparent magnitude of TYC in our filters, we also needed conversion equations which would turn B and V magnitudes into g and r magnitudes[6]:

$$g = V + 0.64(B - V) - 0.13 \quad (1)$$

$$r = V - 0.46(B - V) - 0.11 \quad (2)$$

The apparent magnitude for TYC is found by plugging the magnitudes from SIMBAD into equations, yielding:

$$g = 11.78 + 0.64(12.42 - 11.78) - 0.13 \quad (3)$$

$$g = 12.0596 \approx 12.06 \quad (4)$$

$$r = 11.78 - 0.46(12.42 - 11.78) - 0.11 \quad (5)$$

$$r = 11.6384 \approx 11.64 \quad (6)$$

I will also use the r magnitude for the i filter, as there is no i filter equation and the r and i filters have significant overlap.

Once the calibration star's magnitude is found, I used the magnitude ratio calibration equation to calibrate each image:

$$m_{SNcalibrated} = m_{SNcurrent} \frac{\Sigma m_{current}}{\Sigma m_{reference}} \quad (7)$$

In this equation, the magnitudes on the right side of the equation are both of the reference star, but one is the reference star in the image being calibrated and the other is the reference star in the reference image. Once the images were calibrated, I used the matplotlib, pylab, and numpy python libraries to create light curves for the apparent magnitudes of the supernova in each filter. Once I completed that, I also used the fact that a supernova's peak absolute magnitude is almost always -19.3 to make additional light curves for the absolute magnitudes for the supernova in each filter[3].

The next quantity I calculated was the distance between the Earth and SN 2013aa via the distance modulus equation:

$$m - M = 5 \log_{10} d - 5 \quad (8)$$

where m is the apparent magnitude and M is the absolute magnitude.

Lastly, I used all of the information about SN 2013aa in order to calculate how much Nickel is synthesized by the explosion. In order to calculate the mass of Nickel-56 produced, I first needed to calculate the bolometric luminosity of SN 2013aa using the bolometric luminosity equation:

$$M_{SN} - M_{\odot} = -2.5 \log_{10} \frac{L_{SN}}{L_{\odot}} \quad (9)$$

which gives luminosity in Watts, which is equivalent to $\frac{J}{s}$. Next I found the energy per decay. This was found using the mass difference:

$$\Delta m = m_{Ni^{56}} - m_{Fe^{56}} \quad (10)$$

and by converting this mass difference into energy with the mass-energy equation:

$$E = mc^2 \quad (11)$$

Taking the power, as found in the bolometric luminosity equation, and dividing it by the energy per decay from above gives the decays per second:

$$A = \frac{L_{\odot}}{E} \quad (12)$$

Plugging the decays per second into the following equation yields the total number of radioactive Nickel-56 isotopes:

$$A = \lambda * N \quad (13)$$

where λ can be found from the half life equation, since the half life of Nickel-56 is a known quantity:

$$t_{\frac{1}{2}} = \frac{\ln 2}{\lambda} \quad (14)$$

Finally, I calculated the total mass of Nickel-56 using the following formula:

$$N_{Ni^{56}} * M_{Ni^{56}} = m_{Ni^{56}} \quad (15)$$

where $M_{Ni^{56}}$ is the atomic mass of a Nickel-56 isotope.

3 Data:

I generated the following plots from my data. All plots are normalized and calibrated.

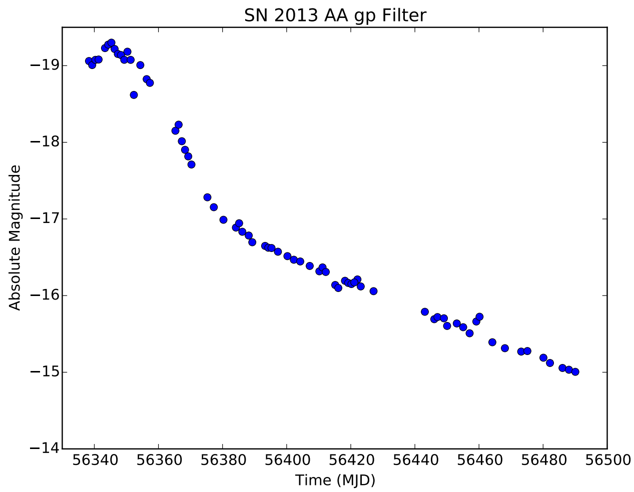

Figure 3: Plot of absolute magnitude versus time through the g filter for SN 2013aa

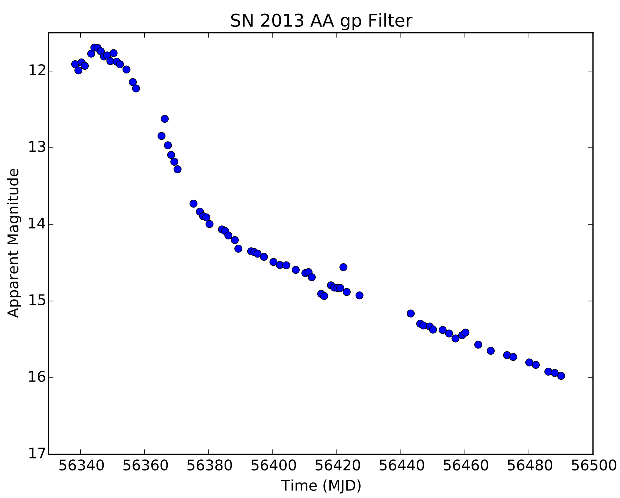

Figure 4: Plot of apparent magnitude versus time through the g filter for SN 2013aa

In the g filter spectrum, the apparent magnitude of SN 2013aa peaked at ≈11.7, which is exactly the apparent magnitude found by the images which discovered it[7]. The g filter plots do not fall off as fast as the other filters, which show that the light radiated by the Cobalt-56 decay into Iron-56 is likely at a blue wavelength, whereas the light radiated by the Nickel-56 decay into Cobalt-56 is more red.

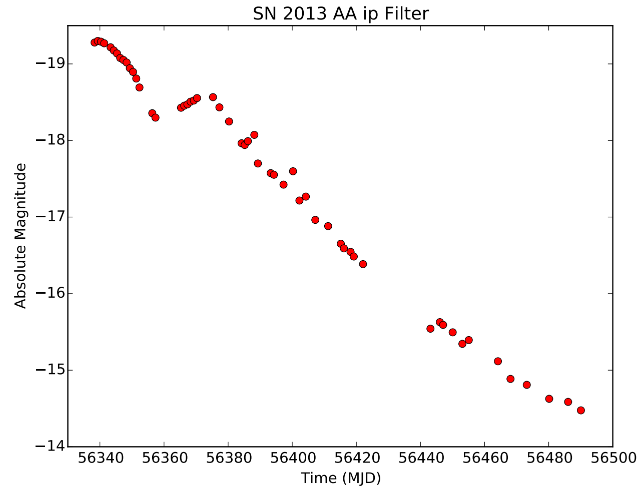

Figure 5: Plot of absolute magnitude versus time through the i filter for SN 2013aa

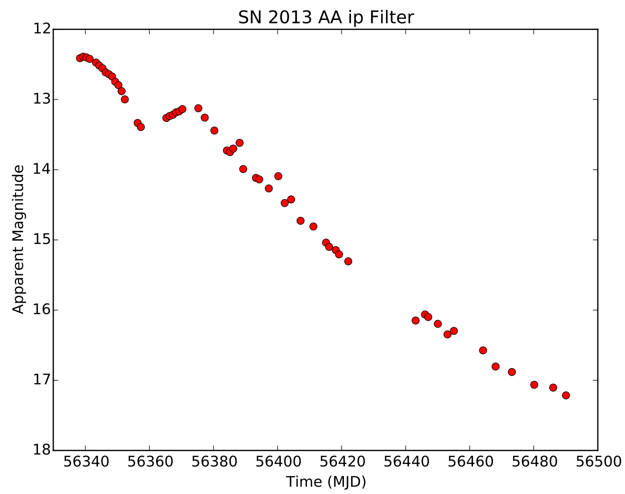

Figure 6: Plot of apparent magnitude versus time through the i filter for SN 2013aa

The apparent magnitude of SN 2013aa in the i filter spectrum peaks at only 12.39, making it slightly dimmer in the i filter than the g filter. This shows that the light emitted by the initial collapse as well as the Nickel-56 decay are both more on the blue side of the visual spectrum. This is likely due to the extreme temperature a supernova produces. Also worth noting about the i filter is that the magnitude actually stops decreasing and begins increasing for a short period of time. This could be an anomaly in the data or could be of physical significance.

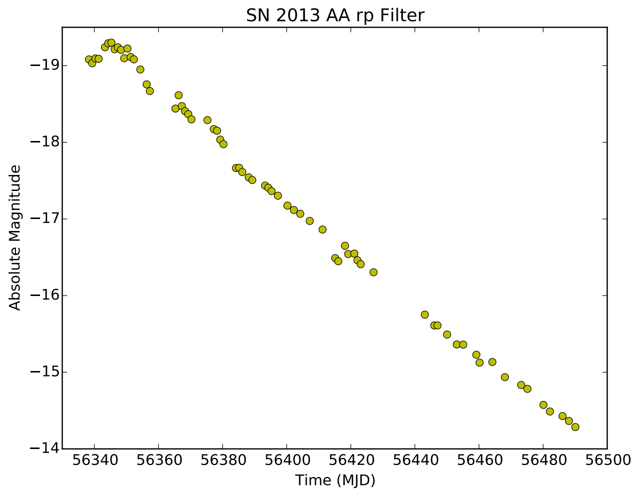

Figure 7: Plot of absolute magnitude versus time through the r filter for SN 2013aa

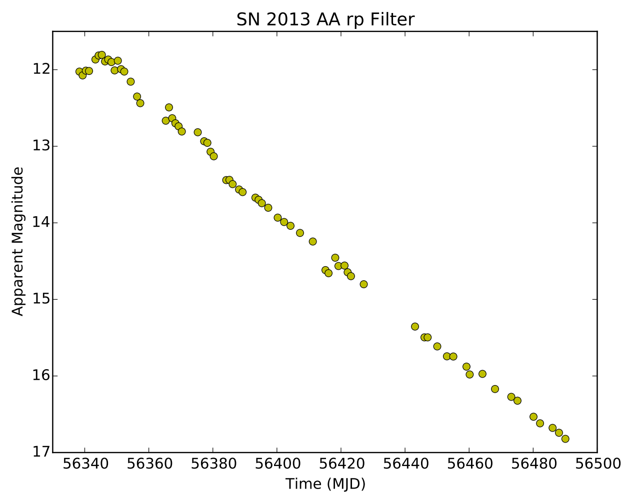

Figure 8: Plot of apparent magnitude versus time through the r filter for SN 2013aa

In the spectrum of the r filter, the apparent magnitude of SN 2013aa peaks at 11.8. This is very slightly less than the g filter peak but larger than the i filter peak, showing that the supernova most likely emitted energy in the infrared spectrum, and probably more than in the red side of the visible spectrum.

4 Analysis:

The maximum peak apparent magnitude of SN 2013aa is known to be 11.7[7], so the distance between Earth and SN 2013aa, therefore, is calculated by the distance modulus equation (8):

$$11.7 - (-19.3) = 5\log_{10} d - 5 \tag{16}$$

$$\frac{36}{5} = \log_{10} d \tag{17}$$

$$d = 10^{7.2} \tag{18}$$

$$d = 15.85Mpc \tag{19}$$

This is very close to the known distance to the supernova's host galaxy, NGC 5643, of 16.9 Mpc. This leaves a percent difference of:

$$Difference = \frac{d_{NGC} - d_{SN}}{d_{NGC}} * 100 \tag{20}$$

$$Difference = \frac{16.9Mpc - 15.85Mpc}{15.85Mpc} * 100 \tag{21}$$

$$Difference = 6.2percent \tag{22}$$

which is very reasonable considering that galaxies can have diameters of hundreds of thousands of parsecs, and that the distance accuracy of a normalized supernova light curve is around 10 percent[9].

In order to calculate the total mass of Nickel-56 isotopes synthesized by the supernova, I first use the bolometric luminosity equation (9) to calculate the power emitted by the supernova at peak magnitude. The relevant constants are:

$$M_{\odot} = 4.83 \tag{23}$$

$$L_{\odot} = 3.846 * 10^{26}W \tag{24}$$

$$M_{SN} = -19.3 \tag{25}$$

Plugging into equation (9) yields:

$$-19.3 - 4.83 = -2.5\log_{10}\frac{L_{SN}}{3.846 * 10^{26}W} \tag{26}$$

$$9.652 = \log_{10}\frac{L_{SN}}{3.846 * 10^{26}W} \tag{27}$$

$$L_{SN} = (3.846 * 10^{26}W) * 10^{9.652} \tag{28}$$

$$L_{SN} = 1.726 * 10^{36}W \tag{29}$$

which is almost 5 billion times as much luminosity is produced by the Sun.

In order to find the energy per decay, I used equation (10):

$$\Delta m = 55.9421324u - 55.93494754u \tag{30}$$

$$\Delta m = 0.0071945u \tag{31}$$

where u is one atomic mass unit, which has a conversion factor to kg of:

$$1u = 1.661 * 10^{-27}kg \tag{32}$$

applying this conversion to Δm gives:

$$\Delta m = 1.194 * 10^{-29}kg \tag{33}$$

Inserting this value into the mas-energy equation (11) yields:

$$E = (1.194 * 10^{-29}kg)(3 * 10^{8}/fracms)^2 \tag{34}$$

$$E = 1.075 * 10^{-12}J \tag{35}$$

which divides into the bolometric luminosity from above to give the decays per second (12):

$$A = \frac{1.726 * 10^{36}W}{1.075 * 10^{-12}J} \tag{36}$$

$$A = 1.606 * 10^{48}\frac{decays}{second} \tag{37}$$

I then have to find the number of molecules, in total, that are synthesized using this value. In order to achieve that, I use the half-life of Nickel-56, known to be 6.077 days[8], to find the decay constant λ (14):

$$t_{\frac{1}{2}} = 6.077days \approx 525053seconds \tag{38}$$

$$\lambda = \frac{\ln 2}{525053seconds} \tag{39}$$

$$\lambda = 1.32 * 10^{-6}\frac{1}{seconds} \tag{40}$$

and now knowing the decay constant, plugging into equation (13) yields:

$$N = \frac{1.606 * 10^{48}\frac{decays}{second}}{1.32 * 10^{-6}\frac{1}{seconds}} \tag{41}$$

$$N = 1.2165 * 10^{55}particles \tag{42}$$

Knowing from calculations above, the mass of one Nickel-56 particle is $9.289 * 10^{-26}kg$, and plugging into equation (15) gives:

$$m_{Ni^{56}} = (1.2165 * 10^{55}particles)(9.289 * 10^{-26}kg) \tag{43}$$

$$m_{Ni^{56}} = 8.28 * 10^{29}kg \tag{44}$$

This is a truly massive amount of Nickel-56 isotopes, but considering how bright a type Ia supernova is, around 5 billion times as bright as the Sun, it is reasonable to expect a large amount of the white dwarf's mass to have been fused into Nickel-56. The total mass of Nickel-56, converted to solar masses ($M_\odot$), is:

$$8.28 * 10^{29}kg = 0.42M_\odot \tag{45}$$

That is nearly half the mass of our own Sun. According to research done on the limit of Nickel-56 produced by this type of supernova, the upper limit on the amount of Nickel-56 produced by this type of supernova is $0.4M_\odot$[10], which is incredibly close to my calculated value. Comparing this number to Earth's mass gives us:

$$8.28 * 10^{29}kg = 1.4 * 10^{5}M_\oplus \tag{46}$$

so the amount of Nickel-56 produced by SN 2013aa is 140,000 times greater than the mass of the Earth.

Knowing that the white dwarf doesn't go supernova until it very nearly reaches the Chandrasekhar limit of $1.4M_\odot$, it is a simple task to calculate the percentage of total mass synthesized by the supernova:

$$\frac{0.42M_\odot}{1.4M_\odot} = 0.3 \tag{47}$$

Thirty percent of the white dwarf's mass was synthesized into radioactive Nickel-56. What is even more amazing is that it is completely synthesized in only about ten seconds.

5 Error Analysis:

There are several sources which may have contributed to reaonable error in this project. First, the atmospheric conditions that the images were taken in may have changed during the time of the observation. This would effect the results a moderate amount because there may be strings of images distorted by clouds, which would diffract and absorb light, obscuring the observatory's view of the supernova and causing its data readings to be lower. The air-density may also have changed, meaning that the air directly in the telescopes line of sight may have been diffracting a one amount of light for some images but a different amount of light for others. Because CCD cameras operate by counting the amount of photons that are absorbed by each pixel of the camera, these possible atmospheric changes could have interfered with enough photons to distort or change certain images. This could cause the noise on the magnitude plots that keep the graph from being completely smooth and continuous. It could also cause some data points to be off in such a way that the peak magnitudes, absolute or apparent, would be off, which would have effected the analysis of the wavelength that Nickel-56 decay emits.

The next possible source of error in this project is my choice of calbiration images and calibration star. If TYC 7818-1832-1 was, perhaps, brighter than I had anticipated and it had overexposed the CCD camera, the flux and magnitude readings that I calibrated every image to would be wrong, which would lead to my images either being washed out and overexposed, or underexposed and lacking contrast. The former of which would cause the magnitude plots to be shorter and wideer, while the latter would cause the magnitude plots to be taller and thinner. Both of these would have negatively impacted my analysis of the wavelength that Nickel-56 decay emits. It would have also changed the apparent magnitude's values, causing me to do calculations with the wrong peak value. Choosing a poor calibration image, such as one that would otherwise be an outlier image due to its relative overall intensity compared to the other images, would have also vastly impacted my graphs and analysis. If any of the images I picked for calibration were highly distorted - perhaps a cloud passed overhead just as the image was taken, leading to lower intensity values for the entire image - my graphs would have been distorted as well, in the same way as picking a poor calibration star would

6 Conclusion

This project's main objective was to take FITS images taken by the LCOGT of supernova SN 2013aa at three wavelengths of light, calibrate the images using photometry software and python tools, and plot the supernova light curves as a function of time. This objective was highly successful. I made six plots of the light curve, two for each filter, and the maximum apparent magnitude reached by the supernova through the g filter, at 11.7, was exactly equal to the known peak apparent magnitude calculated using the discovery images of the supernova[7]. This magnitude, along with the knowledge that type Ia supernovae reach a peak magnitude of -19.3[3], allowed me to calculate the distance to the supernova. I found this distance to be 15.85 Mpc, which, when compared to the 16.9 Mpc distance of its host galaxy NGC 5643, is only a 6.2 percent difference. This difference is well within the 10 percent margin of allowable error for a distance accuracy measurement for a normalized supernova curve[9].

The secondary objective of this project was to use the peak absolute magnitude of this type Ia supernova and use that information to calculate the mass of radioactive Nickel-56 synthesized in the explosion. I found this value to be $8.28 * 10^{29} kg$, which converts to $0.42 M_{\odot}$. which is very close to the $0.4 M_{\odot}$ theoretical limit set forth by gamma ray observations on type Ia supernovae done in 1990[10]. This value becomes more impressive upon converting to fraction of white dwarf mass, which is 0.3. Nearly one third of the total mass of the white dwarf is fused into Nickel-56 during the ten second explosion. Overall, the secondary objective was a resounding success, as the calculated values were very reasonable compared to past data and observations about Nickel-56 synthesis.

References

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