Light Curve of a Type II Supernova

PHYS 134L

The goal of this paper is to summarize the results of having taken many photos of the type II supernova 2022wsp over the course of a month and analyzing these photos to graph the change in the supernova's magnitude over time as a light curve. By doing so, the resulting graph is fitted to a projected graph of known supernovae light curves, and analyzed to determine whether 2022wsp has the potential to become either a black hole or a neutron star.

Introduction:

Supernovae study has always been an extremely interesting and informative area of astrophysics study. From informing us about the expansion of the universe[1] to the rate of its expansion[2], supernovae hide all sorts of secrets in regards to the nature of our universe. Essentially, a supernova is a transient astronomical event that occurs when a star enters the last stage of its evolution. The mass that the star has accrued becomes too much for it to handle, and it collapses in on itself, expanding and eventually exploding. Not all supernovae end up with the same fate. Though they are all caused by an imploding star, the result of said implosion is quite different. Type I supernovae generally leave nothing behind, becoming a large cloud of gas known as a supernova remnant,[3] a subclass of a nebula. Unlike their type I counterparts, type II supernovae leave

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[1] Reiss, A. G.; Filippenko, A. V.; Challis, P.; Clocchiatti, A.; Diercks, A.; Garnavich, P. M.; Gilliland, R. L.; Hogan, C. J.; Jha, S.; Kirshner, R. P.; Leibundgut, B.; Phillips, M. M.; Reiss, D.; Schmidt, B. P.; Schommer, R. A.; Smith, R. C.; Spyromilio, J.; Stubbs, C.; Suntzeff, N. B.; Tonry, J. (1998). Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant. *The Astronomical Journal, Vol. 116, Issue 3,* 1009-1038. https://ui.adsabs.harvard.edu/abs/1998AJ....116.1009R/abstract

[2] Leibundgut, B.; Sollerman, J. (2001). A Cosmological Surprise: The Universe Accelerates. *Europhysics News, Vol. 32, No. 4*. http://www.eso.org/~bleibund/papers/EPN/epn.html

[3] Reynolds, S. P. (2008). Supernova Remnants at High Energy. *Annual Review of Astronomy and Astrophysics, Vol. 46*, 89-126. https://www.annualreviews.org/doi/10.1146/annurev.astro.46.060407.145237

behind a new celestial body in the wake of their expansion, becoming either a neutron star, pulsar, or black hole.

With this distinction between the two main types of supernovae, supernovae light curves have always been a window into the nature of these dying celestial bodies. Type I supernovae have light curves with a sharp maxima that gradually declines, while type 2 supernovae have less sharp of a maxima.[4] There are many ways of graphing these light curves, with simple methods such as downloading data directly from the Kepler satellite and graphing the light curve using this data. Recent developments in this field have even been able to use existing data as well as simulated LSST SNe light curves in order to train a neural network that is able to classify different types of supernovae based on even small sections of light curves[5]. For the purpose of this experiment, Kepler data will not be used, but rather data taken by the LCO SBIG STL-6303 camera. The focus will be the supernova 2022wsp, which is visible over the period 10/19/2022 to 11/19/2022, and is known to be a type II supernova. Another note is that a light curve is generally done over the course of many months. Since the duration of this course does not allow for this, this observational experiment will result in a much more limited light curve with a period of just one month. The hope for this experiment is that the light curves generated from the methods used in this experiment can be fitted to existing light curves of previously examined supernovas to predict whether the supernova will become a neutron star, pulsar, or black hole.

Methods:

Acknowledgement: This work makes use of observations from the Las Cumbres Observatory global telescope network. This paper is based on observations made with the SBIG STL-6303 instrument, using only 0.4m diameter lenses and Bessel B and V filters, operated by Las Cumbres Observatory.

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[4] Woosley, S. E.; Kasen, D.; Blinnikov, S.; Sorokina, E. (2007). TYPE Ia SUPERNOVA LIGHT CURVES. *The Astrophysical Journal, 662,* 487-503. https://iopscience.iop.org/article/10.1086/513732/pdf

[5] Qu, H.; Sako, M. (2022). Photometric Classification of Early-time Supernova Light Curves with SCONE. *The Astronomical Journal, Vol. 163, No. 2*. https://iopscience.iop.org/article/10.3847/1538-3881/ac39a1

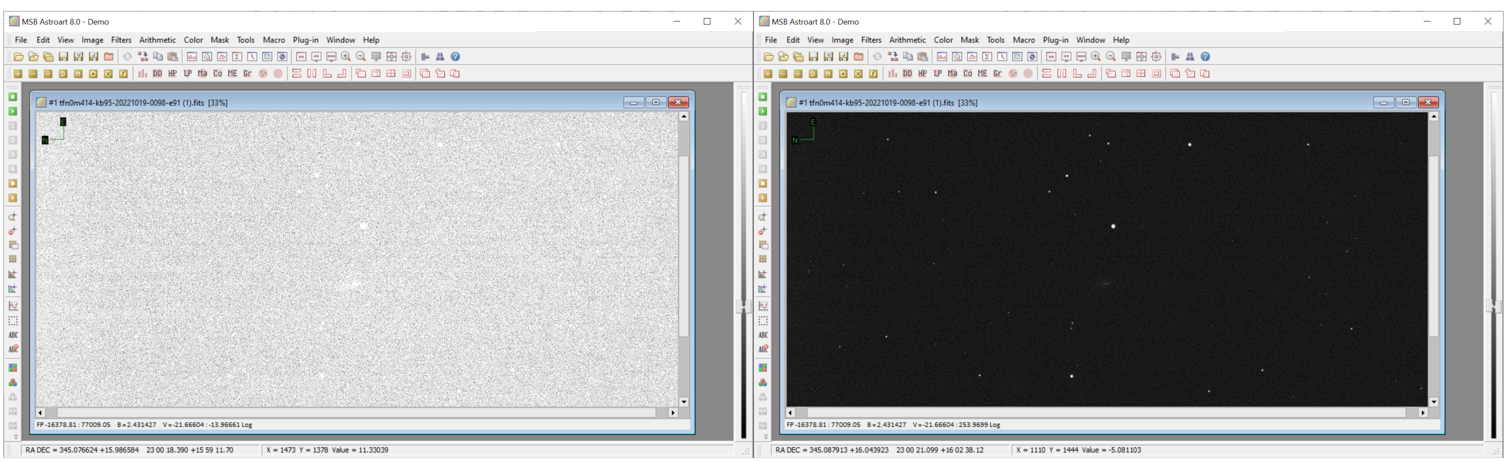
This observational experiment began with an exploration of Purdue University's supernova database: https://www.rochesterastronomy.org/supernova.html. Originally, the experiment was intended to graph two different light curves; one from type I, and another from type II. However, when submitting the LCO request, it was found that the amount of time it would take for both requests would be longer than the allotted time for a request, so the experiment was limited to just graphing the light curve of a type II supernova instead. Upon using the LCO's visibility tool (https://lco.global/observatory/tools/visibility/) with a time frame of 10/19/2022 to 11/19/2022, the type II supernova 2022wsp was decided on. There were other candidates as well, such as 2022aagp, but ultimately 2022wsp seemed to have the highest visibility throughout this time period. The two filters chosen for this observational experiment were Bessel-B and Bessel-V. Multiple filters were chosen just to see if there is any discrepancy between them.

The next step was to do the signal to noise ratio calculation in order to determine the correct exposure time for the LCO camera. The cameras available to students were of a size 0.4m, which after doing a search on the LCO website meant that we would be using the SBIG STL-6303 camera. The documentation and parameters needed for the S/N calculation was found by searching up the correct manual online.[6] Some variables, such as dark current, telescope efficiency, and background flux from sky, used approximated values since they are dependent on the condition of the telescope, which is both unknown to students and potentially variable. The point source signal flux on the telescope was found by converting the 15.4 magnitude of the supernova, which was about 5.43 (photons s^{-1} cm^{-2}). Using Google Sheets to organize my data and calculate using said data, I found that 50 seconds of integration time would yield great results, and optimize the amount of time allowed for the LCO request. At the TA's suggestion, 10 exposures were taken over this integration time, with photos being taken every 2 days.

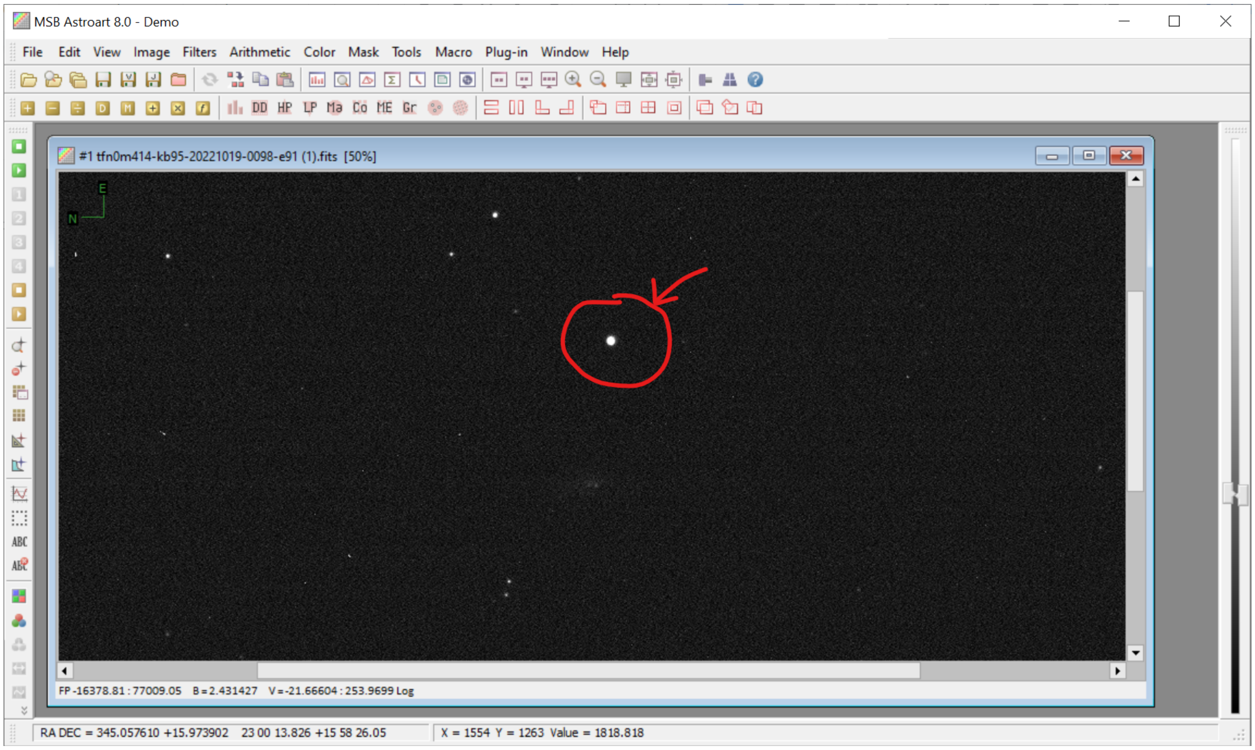
[6] http://www.astro.iag.usp.br/~oc/manuais/STL_6303_manual.pdf

Variable Names	2022wsp		Test from Class Notes
NR (readout noise)	14.5		12
iDC (Dark Current)	1		1
Qe (Quantum Efficiency)	0.475		0.3
F (Point Source Signal Flux on Telescope)	5.43		0.03
Fb (Background Flux from Sky)	0.01		0.01
Ω (Pixel Size)	0.571		4
ε (Telescope Efficiency)	0.5		0.5
t (Integration Time)	50		10
A (Telescope Area)	1294.618917		1000
Nt (Time Dependent Noise per Unit Time)	1672.328585		11.5
S/N (signal to noise ratio)	288.3263043		2.796163947
			correct, expected to be ~2.8

AstroArt 8 was used to determine if the data was usable. Mainly, if the supernova and surrounding stars were visible. Using noise reduction techniques, the image quality is drastically improved:



Seeing that the stars are visible, two more pieces of information are needed: around 4 reference stars and their respective magnitudes and locations, as well as the location of the supernova within the image. Handily, it is pretty easy to find the latter. By right clicking on a star, there is an option to “edit star.” Choosing to do so will reveal the right ascension and declination of the star.



Choosing 4 other stars in the image as reference stars and using the “edit star” function on each of them, their pixel location in the image as well as their right ascension and declination are recorded. Then, using these right ascensions and declinations in the Simbad Database, the magnitudes of these reference stars are recorded.

<u>Method 1: Photometry Code</u>

Now we have all the information we need to use the code. Begin by importing in all the libraries needed for this program. Replace the file name in the variable “imagefile” as needed depending on the .fits file that stores the image of your supernova and its surrounding stars.

```
#First define the image in python as a string.
imagefile = "tfn0m414-kb95-20221019-0098-e91.fits" #Here I am assuming the image is in the same location on my computer as my
# imagefile = r"C:\Users\Sam Whitebook\Test_Image.fits" #Replacing the path with wherever your image actually is. The r is ne

#Now we will use astropy to open the file. Note that sometimes LCO files come with multiple extensions for data and headers.
image = fits.open(imagefile)[0].data
header = fits.open(imagefile)[0].header
```

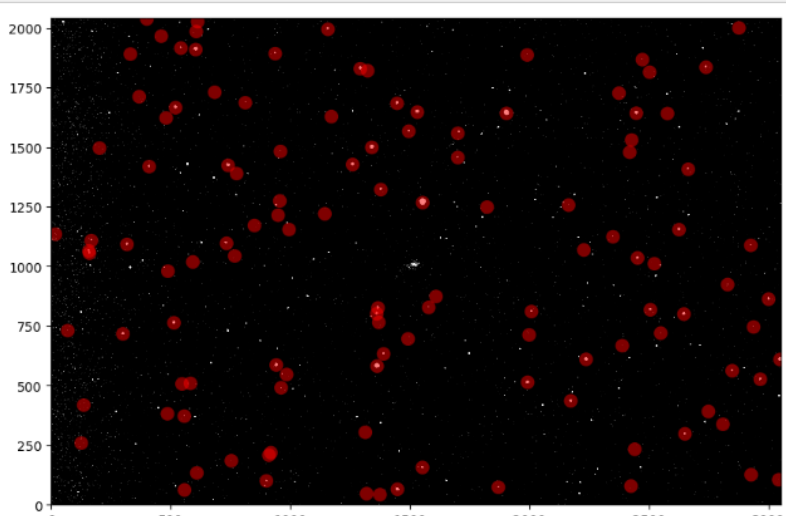
This next section of code helps render the image for the purpose of the program. Vmin and Vmax may have to be changed in order for the image to be rendered well. However, this image still has some background noise.

In [6]:
```
#In order to run photometry we need to first process our images.

#First we ned to do some statistics
sigma_clip = SigmaClip(sigma=3.0) #A sigma clip excludes values that are a certain number of standatd deviations, sigma, abo
mean, median, std = sigma_clipped_stats(image, sigma=3.0) #Here astropy just does some statistics for us. Use the same sigma

bkg_estimator = MedianBackground() #This specifies which method of estimating the background photutils uses. We almost always
bkg = Background2D(image, #Which image to make a background for
                   box_size=(50, 50), #Box size tells the function how much of the image to parse at once. Leave it at 50x50
                   filter_size=(3, 3), #3x3 is default for the filter size. I honestly don't know what a 'median filter' is,
                   sigma_clip=sigma_clip, #Just use the sigma clip we defined earlier.
                   bkg_estimator=bkg_estimator) #Same thing for the background estimator method.
bkg_median = bkg.background_median #This pulls the median of the background values.
```

In [7]:
```
#Now let's find some sources using DAO Star Finder.

daofind = DAOStarFinder(fwhm=5, #This is the full width half maximum of the 'gaussian kernel' of the starfinder in units of p
                        threshold=5*std) #The threshold determines at what pixel value the starfinder will call something a s
sources = daofind(image - bkg_median) #We subtract the median we found earlier from the whole image.
print(sources)
```

These lines of code aim to address this issue, first separating just the background, and then finding the stars in the image from the image generated by the rendered image after subtracting the background image. Now we can superpose the positions of stars with the rendered image, showing this:

In [9]:
```
#Now we know where our sources are, we can do some aperture photometry to get values of their brightness.

positions = np.transpose((sources['xcentroid'], sources['ycentroid'])) #Positions are transposed by default.
apertures = CircularAperture(positions, r=15) #This defines an 'aperture' by radius around each source. The pixel values inst

#Lets plot our image again with the apertures overplotted to see how many stars we found.
plt.figure(figsize=(10,10))
plt.imshow((image), origin='lower', cmap = "gray", vmin=10, vmax = 20)
v = apertures.plot(color='red', lw=5, alpha=0.5) #I define it as a variable to avoid unnecessary readout.
plt.show()
```



Now with this new image, we can conduct photometry on it to find stars within it:

In [10]:

```
#We can make a photometry table using the aperture photometry function.
phot_table = aperture_photometry(image - bkg_median, apertures) #We use the aperture photometry function to list the photon s
print(phot_table)
```

```
 id      xcenter            ycenter          aperture_sum
           pix                pix
--- ------------------ ------------------ -------------------
  1  1375.220444828293  41.92950827854777   -519.9215906041222
  2  1319.407608449426  45.89387700300917   -614.6339640810088
  3  557.5956199560658  61.42952014955083   139.03181126344344
  4 1448.3943815932269    64.459728092626    12643.60218744431
  5 1870.4991027819829  72.80316957913548   1500.2961200424213
  6 2425.3735237860506  77.77425623440787    724.2205811220688
  7  900.1643596219554  99.43911991563226   1776.3416020785664
  8  3043.195365138166 104.24472201952845   122.62823199494412
  9  2927.797231930939 125.37049193636383 -0.26289353786398806
 10  609.1981738983523  133.0031193756406  -273.42768124798863
...                ...                ...                  ...
110   331.287446477776  1889.696574193459   -103.4678837019064
111  937.1319428224134 1891.5712365188508   1544.9699437794993
112  604.8126200507119 1908.5100208551723    23582.20382804785
113  542.6836571103407 1914.8247071642147    630.1502374259874
114   460.491107503513 1964.8906824127755   -606.0597869394113
115  606.8978981799212 1984.1982853007557    598.3223172939199
116 1157.9159347650454 1993.6659151166855   3190.3389649831165
117  2876.998040806492 1999.4499946767617   394.16352907148917
118  612.5853932878122  2025.930984719982    566.3519785098385
119 400.26120955447084 2037.1537492686743    2332.428441952022
Length = 119 rows
```

In [11]:

```
#I will define a function to do all our photometry for us. It appears long, but much of this code can be copy pasted for your

#Most of these black box functions come from astropy stats and photutils. I will briefly explain what they do and what their
def photometry(data, header):
    sigma_clip = SigmaClip(sigma=3.0)
    bkg_estimator = MedianBackground()
    time = header["MJD-OBS"] #I am simply returning the modified julian date off the header for convenience.
    mean, median, std = sigma_clipped_stats(data, sigma=3.0)
    bkg = Background2D(data, box_size=(50, 50), filter_size=(3, 3), sigma_clip=sigma_clip, bkg_estimator=bkg_estimator)
    bkg_median = bkg.background_median
    daofind = DAOStarFinder(fwhm=10, threshold=5*std)
    sources = daofind(data - bkg_median)
    positions = np.transpose((sources['xcentroid'], sources['ycentroid']))
    apertures = CircularAperture(positions, r=15)
    phot_table = aperture_photometry(data - bkg_median, apertures)
    aperture_sums = phot_table['aperture_sum']
    return time, positions, aperture_sums
```

That was a lot. Lets call our photometry function on our image and see what it finds.

In [12]:

```
time, positions, sums = photometry(image, header)
print("We found", len(sums), "stars")

#Lets call a random star and see what information we found on it.
star_index = np.random.randint(0,len(sums))
star_position = positions[star_index]
star_photons = sums[star_index]
print("The star's pixel position is", star_position)
print("The star's photon count is", star_photons)
```

```
We found 133 stars
The star's pixel position is [2867.43285959 2039.85518625]
The star's photon count is 993.5910662100683
```

Now that the program can recognize the position of the stars within the image you give it, the program can find the zero point correction from the reference stars, as well as the magnitude of the supernova:

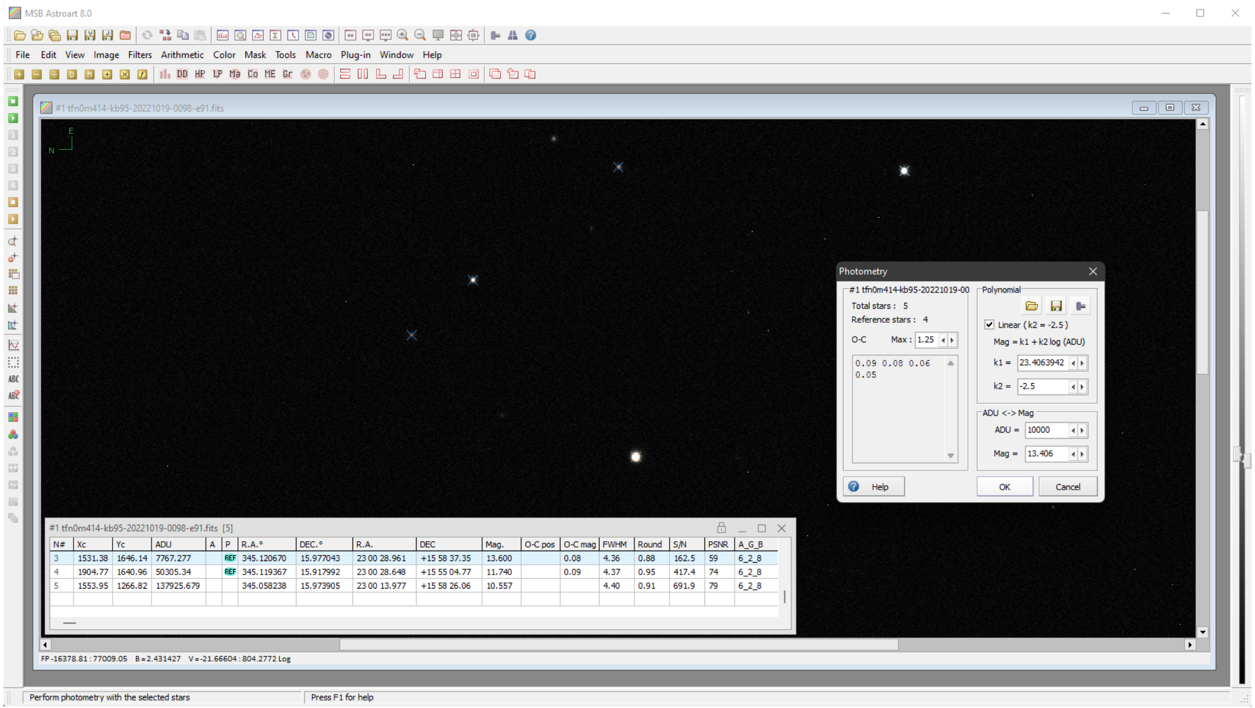
```
In [13]:
phot_x = phot_table['xcenter']
phot_y = phot_table['ycenter']
phot_flux = phot_table['aperture_sum']
star_coords = [[1554,1267]] #I find these coordinates by hand in SAO DS9
calstar_flux = []
for j in range(len(star_coords)): #This Loop finds the Location of each star in our image, matching it to the coordinates we
    r = np.sqrt((phot_x.value - star_coords[j][0])**2 + (phot_y.value - star_coords[j][1])**2)
    print(np.min(r)) #You should print out your minimimum distance to ensure you are actually finding the right star. This vc
    index = np.where(r == np.min(r))[0][0]
    calstar_flux.append(phot_flux[index])

calstar_mag = -2.5*np.log10(calstar_flux)

# calibrate with 4 other stars first, then repeat for just the supernova and add the ZP from the 4 stars to the magnitude of

print("Our calibration magnitudes are", calstar_mag)
sky_map = [15.4]
difference = sky_map - calstar_mag
print("The difference between our accepted and found magnitudes is", difference)
ZP = np.mean(difference)
print("Our Zero Point is then", ZP)
```

```
0.39642404477626814
Our calibration magnitudes are [-13.56359791]
The difference between our accepted and found magnitudes is [28.96359791]
Our Zero Point is then 28.96359791474979
```

Finally, the magnitude of the supernova in the image will be equal to the difference between the calculated magnitude and the zero point correction. This process will be repeated for each of the images the LCO has taken. Given that 2 different filters are being used, and there will be 15 total days during the allotted period with an image being taken each of those days, there should be 30 data points in total, with a graph of 15 points from both Bessel-B and Bessel-V.

<u>Method 2: AstroArt8 Tools</u>

The second method that will be used to find the relative magnitude of the supernova will be done directly in AstroArt8 by using the built in tools. Using the same reference stars as in the previous method, select the stars in the image in AstroArt, and open the “stars” function under the “view” tab. Then, using the SIMBAD star database, manually set the magnitudes of these stars based on what filter the image was taken with. Make sure these stars are set as reference stars as well. Once this is done, click on the supernova in the image. Under the “tools” tab, click the “photometry” function. It should say both the amount of reference stars selected, as well as the total number of stars being analyzed. I chose to use a linear fit to avoid overfitting. The program should then tell you the relative magnitude of the supernova based on the reference stars.



Results:

2022wsp reference stars chosen for calibration:

Star Location	Bessel-B Magnitude	Bessel-V Magnitude
23 00 20.353 +16 01 12.25[7]	14.1	13.7
23 00 23.171 +16 00 26.30[8]	12.9	12.4
23 00 28.961 +15 58 37.35[9]	13.6	13.2
23 00 28.648 +15 55 04.77[10]	11.74	11.16

2022wsp Method 1:

Date	Zero Point Correction	Bessel-B magnitude	Bessel-V magnitude
10/19/22	28.964	12.326	11.560
10/21/22	27.432	12.157	11.534
10/23/22	26.786	12.425	11.838
10/25/22	Not Visible	Not Visible	Not Visible
10/27/22	28.456	12.712	11.909
10/29/22	28.941	12.835	12.033
10/31/22	24.509	12.637	11.991
11/2/22	26.342	12.498	11.873
11/4/22	No Image Taken	No Image Taken	No Image Taken
11/6/22	25.768	12.523	11.898

[7] Khrutskaya E. V.; Khovritchev M. Y.; and Bronnikova N. M. (2004). The Pul-3 catalogue of 58483 stars in the Tycho-2 system. *Astronomy and Astrophysics, vol. 418*, 357-362. https://simbad.cds.unistra.fr/simbad/sim-ref?bibcode=2004A%26A...418..357K

[8] Rybka S. P.; Yatsenko A. I. (1997). GPM - compiled catalogue of absolute proper motions of stars in selected areas of sky with galaxies. *Kinematika Fiz. Nebesn. Tel., 13, No. 5,* 70-74. https://simbad.cds.unistra.fr/simbad/sim-ref?bibcode=1997KFNT...13e..70R

[9] Khrutskaya E. V.; Khovritchev M. Y.; and Bronnikova N. M. (2004). The Pul-3 catalogue of 58483 stars in the Tycho-2 system. *Astronomy and Astrophysics, vol. 418*, 357-362. https://simbad.cds.unistra.fr/simbad/sim-ref?bibcode=2004A%26A...418..357K

[10] Rybka S. P.; Yatsenko A. I. (1997). GPM - compiled catalogue of absolute proper motions of stars in selected areas of sky with galaxies. *Kinematika Fiz. Nebesn. Tel., 13, No. 5,* 70-74. https://simbad.cds.unistra.fr/simbad/sim-ref?bibcode=1997KFNT...13e..70R

11/8/22	28.756	12.614	11.904
11/10/22	27.668	12.432	11.637
11/12/22	28.342	12.498	11.934
11/14/22	25.148	12.721	12.292
11/16/22	27.365	12.567	11.957
11/18/22	28.291	12.482	11.886

2022wsp Method 2:

Date	Bessel-B magnitude	Bessel-V magnitude
10/19/22	10.557	10.348
10/21/22	10.630	10.312
10/23/22	10.632	10.322
10/25/22	Not Visible	Not Visible
10/27/22	10.602	10.354
10/29/22	10.549	10.353
10/31/22	10.519	10.239
11/2/22	10.592	10.312
11/4/22	No Image Taken	No Image Taken
11/6/22	10.638	10.331
11/8/22	10.639	10.351
11/10/22	10.594	10.316
11/12/22	10.762	10.424
11/14/22	10.640	10.334
11/16/22	10.614	10.325
11/18/22	10.564	10.316

2022wpy Method 2:

Date	Bessel-V magnitude
10/27/22	12.819
10/28/22	12.683
10/30/22	12.913
11/1/22	13.257
11/3/22	13.301
11/5/22	13.496
11/10/22	13.673
11/11/22	13.545
11/14/22	14.185

Error approximation:

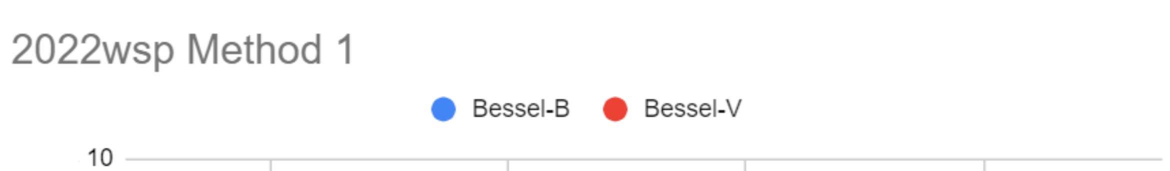
For method 1, since the program takes the average magnitudes of all the reference stars used in the photo, the error can be given by the standard deviation of the magnitudes of the reference stars used. With this, we find the error in the Bessel-B filter to be 0.8858 and the error in the Bessel-V filter to be 0.9595.

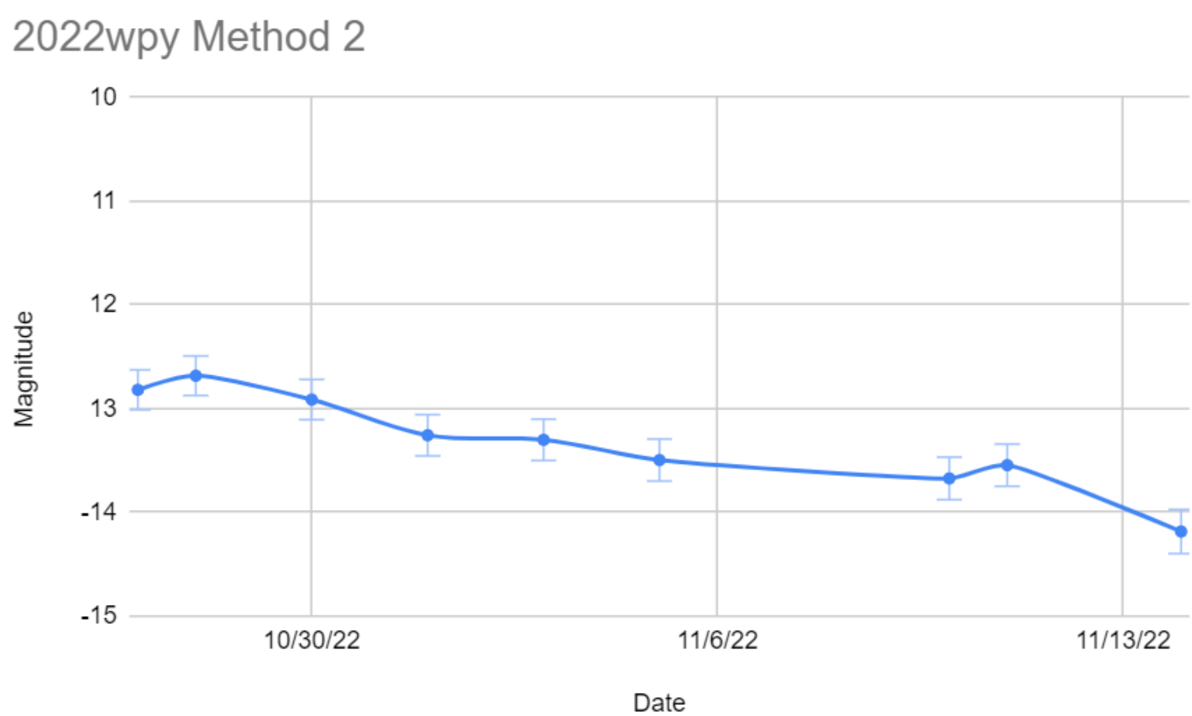
The method by which AstroArt8 calculates its magnitudes through photometry is uncertain, so for method 2, the uncertainty is calculated through the root 12 rule. Although AstroArt8 measures up to the thousandth, the reference magnitudes were from SIMBAD, which measures to the tenth, so 0.09 is used as Δ.

$$\sigma = \frac{1}{\sqrt{3}}\left(\frac{\Delta}{2}\right) = \frac{\Delta}{\sqrt{12}}$$

With this, the error for method 2 is calculated to be 0.026 at each point.

Light curves:

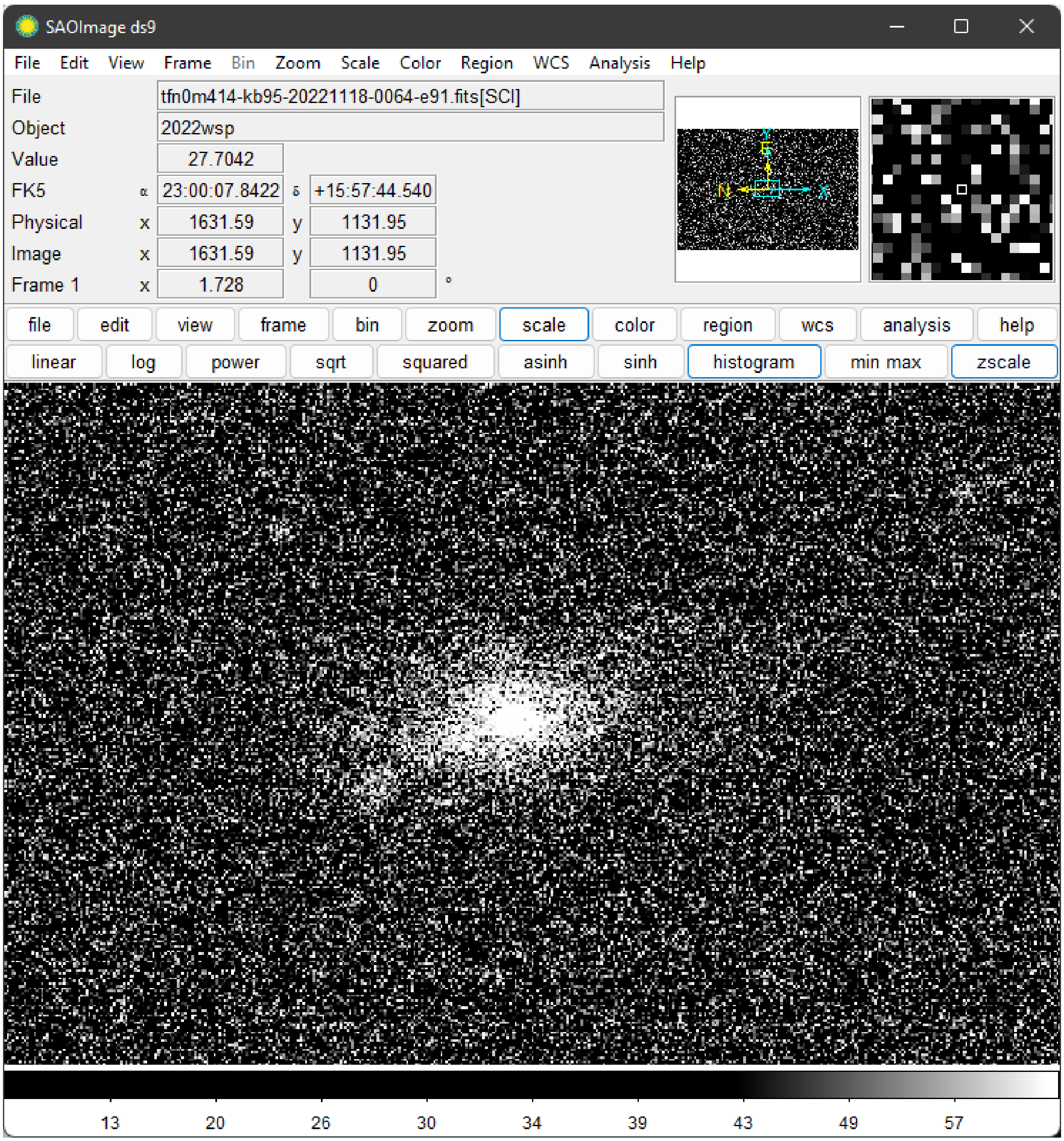




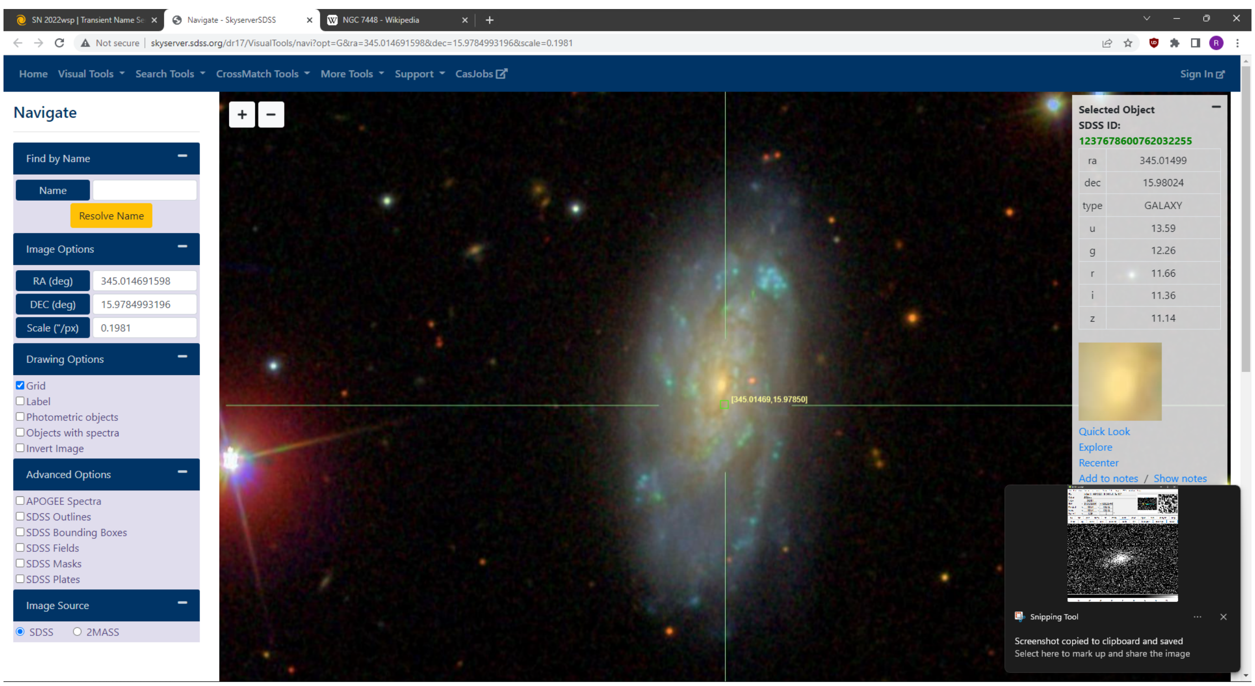
2022wpy Method 2
Magnitude
10
11
12
13
-14
-15
10/30/22
11/6/22
11/13/22
Date

Discussion:

Unexpectedly, the light curve graphs of 2022wsp show fluctuations of magnitude around a single magnitude, rather than a gradual downwards slope as imagined. To understand this issue, the LCO images were inputted into DS9, an image display and visualization tool for astronomical data.



Upon closer inspection, the bright concentration of pixels at the center of the image was not in fact the supernova, but rather the center of the galaxy in which the supernova was located, NGC 7448. The actual supernova itself is a little bit to the bottom right of the center concentration, barely visible. As such, this would explain why the light curves showed fluctuations within a small range of magnitudes, and with such consistency across methods and filters. This conclusion is confirmed by using the Sloan Digital Sky Survey image database. Searching for 2022wsp shows that the supernova 2022wsp is indeed extremely close to the center of the galaxy NGC 7448, making the galactic core indistinguishable from the supernova since they are too close in angular proximity:



To make up for this error, data for the type 1A supernova 2022wpy was borrowed from another experiment group, since there was no more time to take new data. The third graph labeled “2022wpy Method 2” in the results section of this paper is the outcome of using AstroArt8’s built in photometry function to calculate the magnitude of 2022wpy over time, and shows a gradual downwards slope in magnitude as expected of a supernova light curve. Looking at this new light curve, it is still extremely difficult to determine the stage at which the supernova is in its life. Since it just shows a general downwards slope, this would be placed anywhere on a model light curve, and is therefore not indicative of a specific time frame for the supernova.

Future experiments of this nature could benefit from a larger time frame, as the larger sample size would allow for a much more accurate representation of the light curve of a supernova. Perhaps images could be taken more frequently as well for a more detailed light curve. An improvement to be made prior to requesting LCO images would be to check the angular proximity of the supernova to other celestial bodies near it, as this proved to be a sticking point for this particular interaction of the experiment. Another improvement would be to create a code that would separate all the stars from the image except for the supernova, and use those all as reference stars. One of the main issues involved with this version of the experiment was the time consumed by having to manually search up star positions and their respective magnitudes. By automating this process, not only will the process of analyzing an image be faster, but the zero point correction may be more accurate as well, leading to a more accurate representation of the magnitude of the supernova in the image.