

An Examination of Various Supernovae: Classification and Light Curves

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Abstract

This paper presents photometry data for multiple supernovae: 2023ixf, AT2023gvj, 2023gfo, and 2023foa. These observations were made utilizing a 0.4-meter SBIG STL6303 telescope operated by Las Cumbres Observatory. They were taken using various filters, including SDSS u, g, r, and i. Using these observations, we were able to see the expected relationship of a supernova's photometry data to its, but not exact claims about the type of the AT2023gvj, which is still unknown. We were also able to construct a light curve for the brightest of the four supernovae and found that it peaked around 6/4/2023, which coarsely matches up with data from other scientists.

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1 Introduction

Supernovae, the spectacular explosion that signifies the end of a star's life cycle. These events have captured the attention of astronomers for centuries due to how much information they can give us about the universe. Scientists have used data gathered from supernovae to explain the origins of heavy elements [5] and black holes [3], as well as to gain some insight into how our own solar system was formed [1].

1.1 Types of Supernova

While a supernova will always mean the end of a star's life, the specific behavior leading to and following the supernova can vary significantly. To describe these differences, supernovae are assigned to different categories [4], often based on their observed spectra. The first coarse categorization is between type I and type II (type 1 and 2) supernovae, with the most important distinction being that type I supernovae do not show hydrogen while type II do. A finer categorization is then done within these categories.

Within type I supernova, we have type Ia, Ib, and Ic, which all do not show hydrogen. Type Ia supernovae are further categorized by a singly ionized silicon line at 615 nanometers. This type of supernova is also interesting due to its unique cause, a thermal runaway caused by the core of the star being heated to a point where carbon fusion is ignited, thus leading to a runaway nuclear fusion. Type Ib and Ic, on the other hand, do not show a silicon line; instead, type Ib shows a non-ionized helium line at 588 nanometers, whereas type Ic does not. These and the rest of the supernova types are all thought to be caused by core collapses.

Within type II supernova there are types IIb, II-P, II-l, and IIIn supernova. Starting off, IIb is different than other type II supernovae due to its change in spectrum, causing it to look like a type Ib spectrum over time. The next distinction is IIIn supernova which have narrow hydrogen lines in the spectrum. Finally, type II-P and II-L supernovae are differentiated by their light curves, where type II-P reaches a plateau in its curve, whereas type II-L decreases linearly over time.

1.2 Light Curves

Another important aspect of supernovae is how they evolve over time. One of the ways this is studied is through creating light curves, which measure the brightness of a supernova over time [2]. As mentioned before, these curves are an important part of the finer classification of supernovae. To add to this, the light curves of the coarse categories allow us to make further conclusions about the universe. For example, due to the sharp maxima of Type I supernovae with a gradual decline, they are perfect to use as standard candles, which are indicators of astronomical distances. Furthermore, these curves also offer us insight into the star before it became a supernova and into the reasons supernovae happen at all.

2 Methods

In order to try to classify supernovae and create a light curve, we completed the following steps:

2.1 Data Acquisition

Data was collected using a telescope from the Las Cumbres Observatory (LCO) global telescope network. Specifically with a model SBIG STL-6303 telescope (0.4-meter diameter lenses). Data was collected with SDSS u, g, r, and i filters, with varying exposure times. Using an online supernova database created by David Bishop [6], we initially found 3 suitable supernovae: AT2023gvj, 2023gfo, and 2023foa. We chose these supernovae as their magnitudes were at a maximum of 16.5, with 2 out of 3 being considerably lower. Furthermore, we also chose one known supernova from each type, as well as one unknown at the time, so that we could attempt to classify the type of the unknown supernova. Luckily during our time in this course, a fourth supernova, 2023ixf, was discovered with a magnitude of 10.9, considerably higher than the others we observed. To add on, while we submitted requests for all 4 supernovae, we only used data from those requests for the original three supernovae and instead used data being collected by Samuel Whitebook for 2023ixf as he was taking significantly more data than we would have been able to with the time allotted for our class. Exposure times were based on SNR calculations and information provided by LCO. This led to slight differences in what data was collected for different supernovae; the details are given in Table one.

Name	R.A.	Dec	Magnitude (from database)	Type (from database)	Filter (SDSS)	Exposure Time τ
AT2023gvj	14:55:34.426	-15:34:19.00	15.4	unknown	u,g,r,i	250,100,100,100
2023gfo	13:09:39.677	-07:50:11.75	15.3	II	u,g,r,i	250,100,100,100
2023foa	17:03:59.300	+24:11:10.57	16.2	Ia	u,g,r,i	250,100,100,100
2023ixf	14:03:38.562	+54:18:41.94	10.9	III	r,i	15,15

Table 1: Supernova Data Information

2.1.1 SNR Calculation

As mentioned previously, we completed a signal-to-noise ratio (SNR) calculation in order to choose an optimal exposure time. Using the following equations (parameters defined in table two) [7]:

$$S = F\tau A\epsilon Q_e \quad (1)$$

$$N = (N_R^2 + \tau(i_{DC} + F_\beta A\epsilon Q_e \Omega))^{1/2} \quad (2)$$

Variable	Description	Value Used
F	Flux from the target	$3 * 10^6 * 10^{-\frac{2m}{5}}$
A	Telescope area	$\pi * 20^2$
τ	Integration time	Unknown
ϵ	Telescope transfer efficiency	.5
Q_e	Quantum efficiency	.3
N_R	Readout noise	14.5
i_{DC}	Dark Current	0.03
F_β	Background flux	0.1
Ω	Angle of pixel	0.571

Table 2: SNR Calculation Parameters, taken from LCO

With this, we were able to produce an SNR vs τ plot for each given magnitude and choose a sufficient τ or integration time. We confirmed this integration time with the graph provided by LCO (figure 1):

Exposure time estimation for SBIG 6303 LCO @ 0.4m telescopes Point Sources

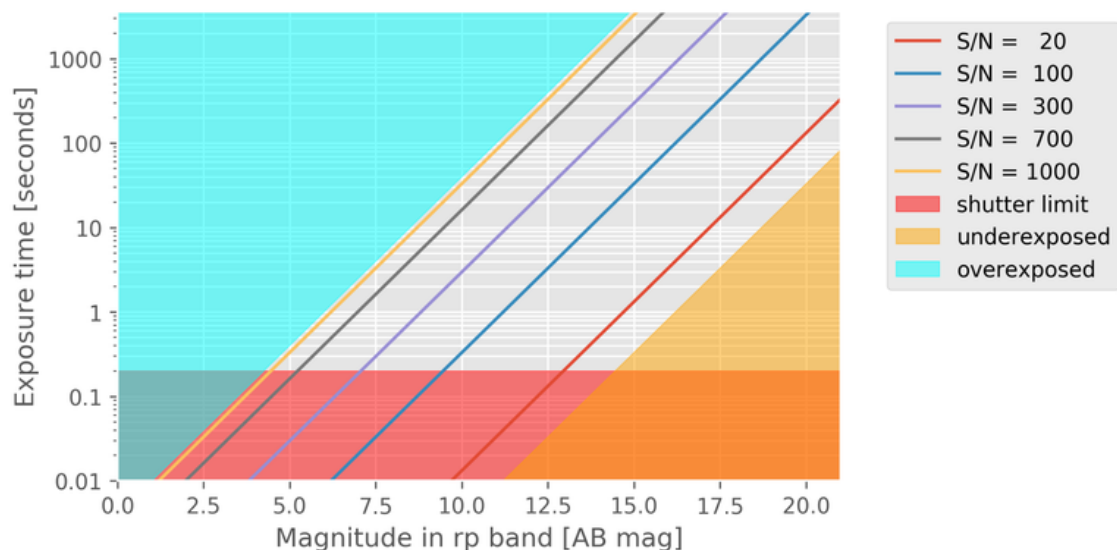


Figure 1: LCO Exposure Time (τ) Measurements

2.2 Pre-processing Data

After collecting the data, we completed a preprocessing step before analysis. To complete this, we used Astroart 8. Using this, we stacked the multiple exposures taken around the same time in order to further reduce the noise. The stacking was aligned through a translation using the auto-align function, any satellite streaks were also removed. An example of the pre- and post-processed images is shown in figures two and three.

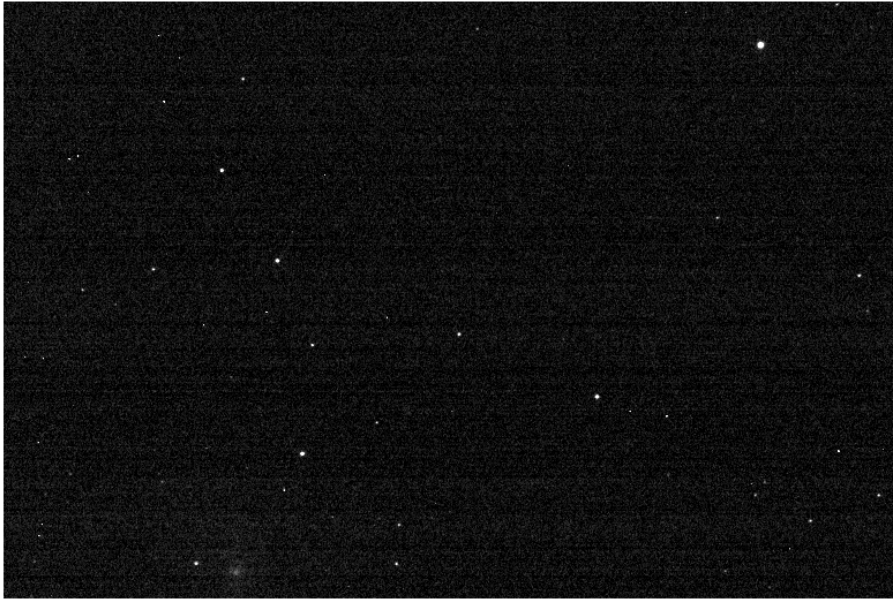


Figure 2: Pre-processed image UPDATE



Figure 3: Post-processed image UPDATE

2.3 Extracting the relevant data

Our initial goals were to:

1. Make sure we were able to capture the star.
2. Find the exact magnitudes of the star.

Starting with how we achieved our first goal: We started with Sam's photometry function, which used DAOSTarFinder, a function from Astropy [8] that takes in an image and returns the positions and aperture sums of stars it is able to find in the image. We modified this function to remove all stars with negative aperture sums (which were interpreted to be from noise in the image). We also modified the function to return not only the pixel locations of the stars, but the world coordinates that correspond to these pixel locations (using information from the fits header) as well. The exact function is shown below:

```
def photometry(data, header, fwhm=5, thresh=5):  
    sigma_clip = SigmaClip(sigma=3.0)  
    bkg_estimator = MedianBackground()  
    time = header["MJD-OBS"]  
    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=fwhm, threshold=thresh*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']

posipos=np.where(aperture_sums>0)[0]

astropycoords=[]

wcs = WCS(header)

positions=positions[posipos]

aperture_sums=aperture_sums[posipos]

for i in range(len(positions)):

    astropycoords.append(wcs.pixel_to_world(positions[i,0],positions[i
                                                ,1]))

return time, positions, aperture_sums, astropycoords

```

We are able to use these locations to plot the stars. We also mark the location of the observed star on the image and compare the plotting code and produced image shown below:

```

time, positions, aperture_sums, astropycoords=photometry(image, header,
                                                         fwhm=5, thresh=7)

plt.figure(figsize=(10,10))

plt.imshow(image_to_plot, origin='lower', cmap = "gray", vmin=0, vmax =
                                                100)

circle2 = plt.Circle([int(coords_pixels[0]),int(coords_pixels[1])], 30,

```

```

        color='b', fill=False)

plt.gca().add_patch(circle2)

apertures = CircularAperture(ref_star_locs, r=15)
v = apertures.plot(color='pink', lw=5, fill=False)

apertures = CircularAperture(positions, r=15)
v = apertures.plot(color='red', lw=5, alpha=0.5)

plt.show()

```

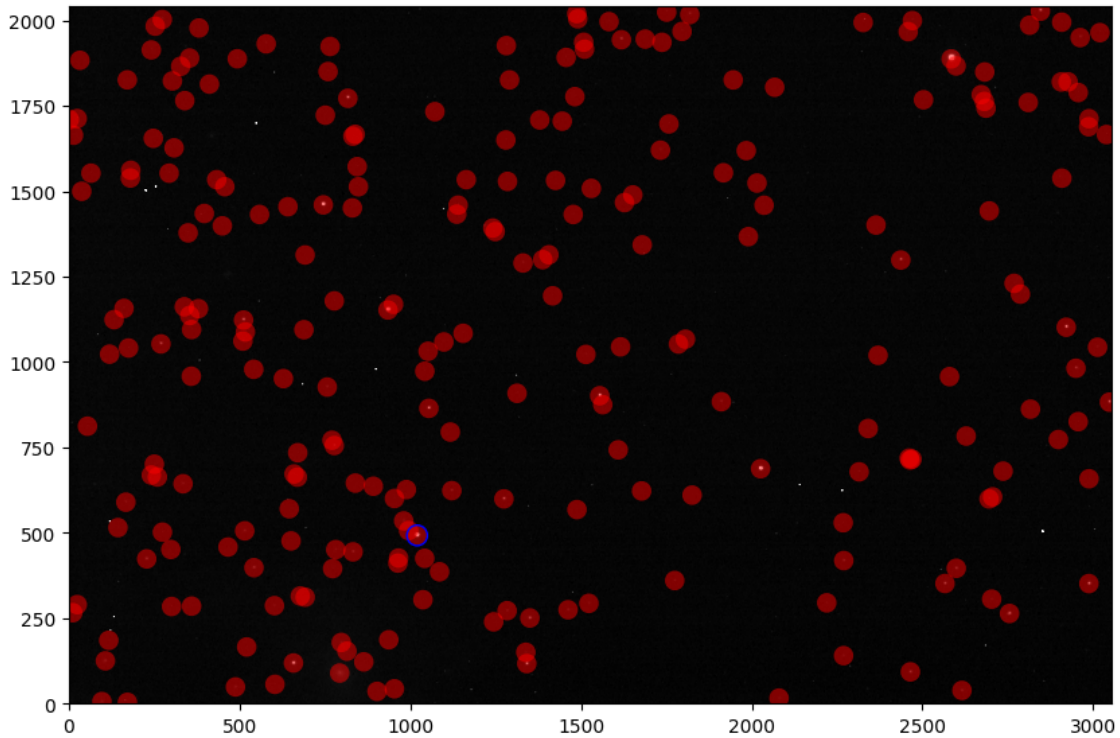


Figure 4: Transparent red circles mark detected stars with the blue circle matching the star of interest

We now continue to our second goal of finding the exact magnitudes. To achieve this, we first take the world coordinates of the stars we found in our image and passed them through the SDSS database returning the magnitudes and errors in those magnitudes of

nearby reference stars in the relevant filters. Finally, the magnitudes of these reference stars were used to calculate a zero-point, which we then used to get the exact magnitude of the supernova (rather than the relative magnitude that the data provides). Again the exact code is shown below, as well as an example output:

```
result = SDSS.query_crossid(astropycoords, photoobj_fields=['ra','dec','
                                                                psfMag_'+filter_chosen,'psfMagerr_'+
                                                                filter_chosen],radius=5*u.arcsec)

ref_star_data=[]
for i in range(len(result)):
    if result['type'][i]=='STAR' and result['psfMag_'+filter_chosen][i]<16:
        ref_star_data.append(result[i])
ref_star_data=vstack(ref_star_data)
ref_star_locs=[]
ref_star_mags=[]
ref_star_err=[]
for i in range(len(ref_star_data)):
    ref_star_mags.append(ref_star_data['psfMag_'+filter_chosen][i])
    ref_star_err.append(ref_star_data['psfMagerr_'+filter_chosen][i])
    ref_star_locs.append(wcs.world_to_pixel(SkyCoord(ref_star_data['ra'][i],
                                                    ref_star_data['dec'][i], frame='
                                                    icrs', unit='deg'))))
ref_star_locs=np.array(ref_star_locs)
ref_star_mags=np.array(ref_star_mags)
ref_star_err=np.array(ref_star_err)
phot_x = positions[:,0]
```

```

phot_y = positions[:,1]
phot_flux = aperture_sums
calstar_flux = []
for j in range(len(ref_star_locs)):
    r = np.sqrt((phot_x - ref_star_locs[j][0])**2 + (phot_y -
                                                    ref_star_locs[j][1])**2)

    index = np.where(r == np.min(r))[0][0]
    calstar_flux.append(phot_flux[index])
r = np.sqrt((phot_x - coords_pixels[0])**2 + (phot_y - coords_pixels[1])
            **2)
index = np.where(r == np.min(r))[0][0]
a=phot_flux[index]
calstar_mag = -2.5*np.log10(calstar_flux)
roi_mag=-2.5*np.log10(a)
print("Our calibration magnitudes are", calstar_mag)
difference = calstar_mag - ref_star_mags
print("The difference between our accepted and found magnitudes is",
      difference)

ZP = np.mean(difference)
print("Our Zero Point is then", ZP)
print("So our roi mag is then ",roi_mag-ZP)

```

Example Output:

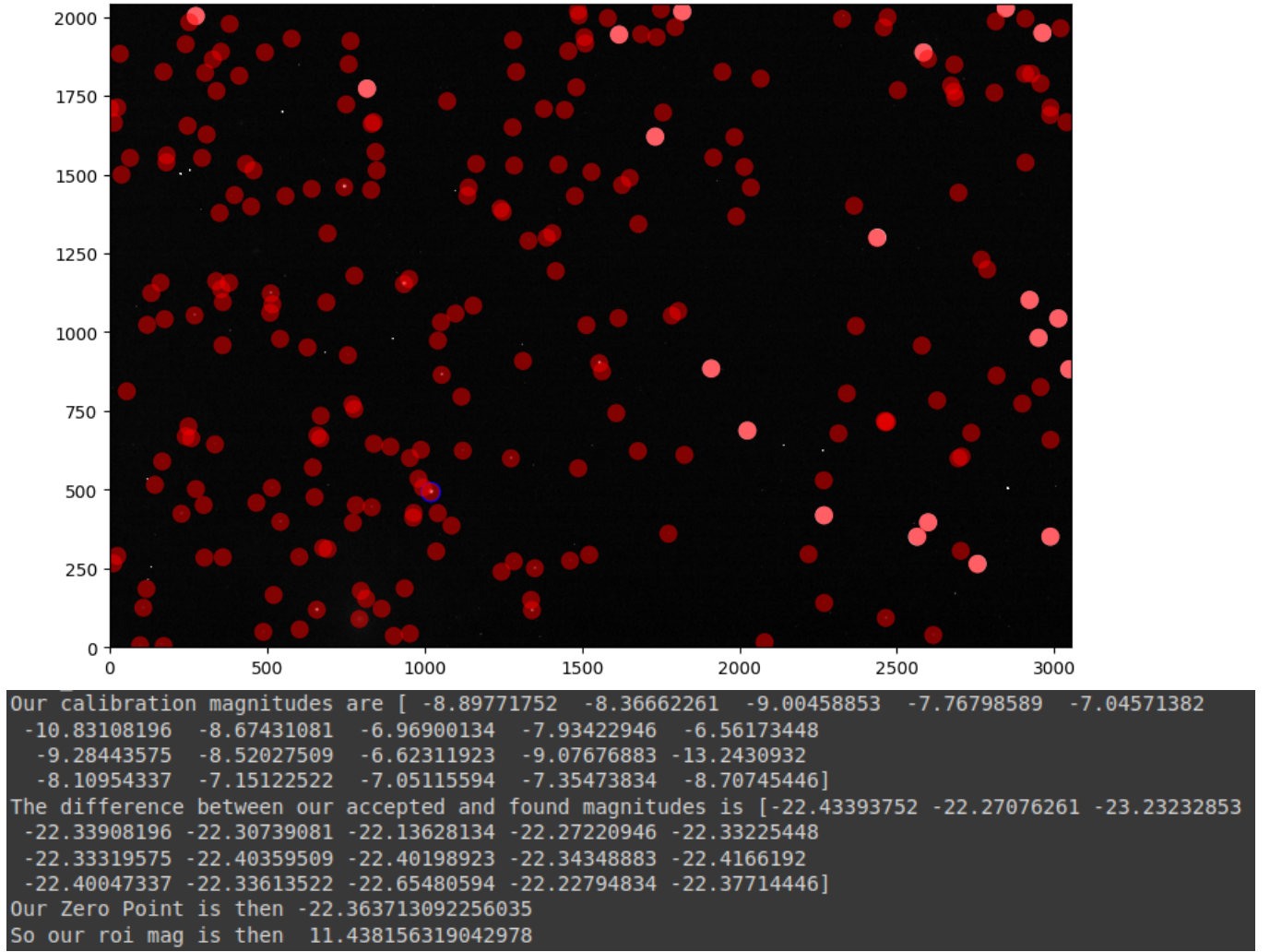


Figure 5: Text and image output, reference stars in pink

This concludes our methods, and we will now use this extracted data to investigate the details of the supernovae.

3 Results

3.1 Quick Aside: Astrophotography

Before we present our main results, we present two astrophotography projects we completed. The first is of the Cat's Eye Nebula, chosen as it is thought to come from a dying star similar to supernovae. The second is of the galaxy hosting our brightest supernova, M101. The two images are pictured in Figures six and seven below:

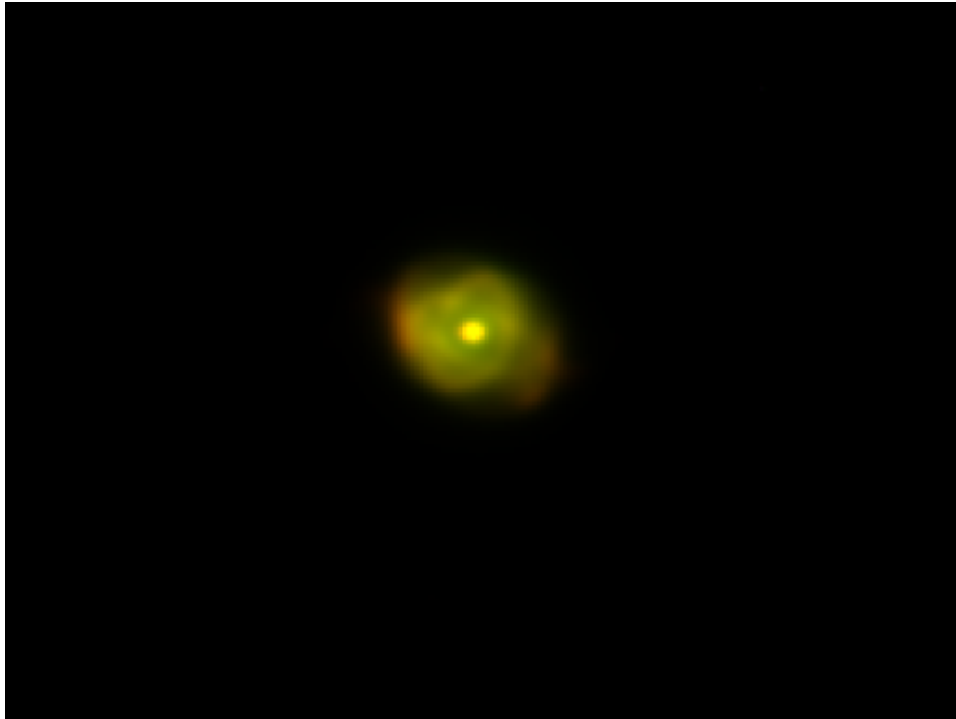


Figure 6: Cat's Eye Nebula



Figure 7: M101

3.2 Classification

For two of our supernovae, we are unable to report the exact magnitude due to not being able to find reference stars in the taken images. We still report the relative magnitudes from the data. We also were unable to find the supernova in the data taken from the u-band filters. We report our findings in Table 3:

<u>2023ixf (IIL)</u>	g-band	r-band	i-band
Exact magnitude (zero-point corrected)	N/A	11.24	11.44
Zero-point	N/A	-22.36	-24.38
Error (Standard-error of zero-point, $\frac{\sigma}{n^{\frac{1}{2}}}$)	N/A	0.055	0.046
Relative magnitude	N/A	-11.12	-12.94
<u>2023foa (Ia)</u>	g-band	r-band	i-band
Exact magnitude (zero-point corrected)	17.51	17.26	16.46
Zero-point	-26.39	-26.52	-25.78
Error (Standard-error of zero-point, $\frac{\sigma}{n^{\frac{1}{2}}}$)	0.037	0.039	0.049
Relative magnitude	-8.88	-9.26	-9.317
<u>AT2023gvj (Unknown)</u>	g-band	r-band	i-band
Relative magnitude	-10.78	-12.26	-12.14
<u>2023gfo (II)</u>	g-band	r-band	i-band
Relative magnitude	-11.47	-12.25	-11.76

Table 3: Magnitude Information

Unfortunately, due to a combination of factors such as not having reference stars for some of the supernovae and the filters used being wider-band than is ideal, we are unable to make any exact predictions about the type of the unknown supernova. We comment further on these issues and speculate in the Discussion.

3.3 Light Curve

We were also able to construct a brief light curve for the brightest supernova 2023ixf:

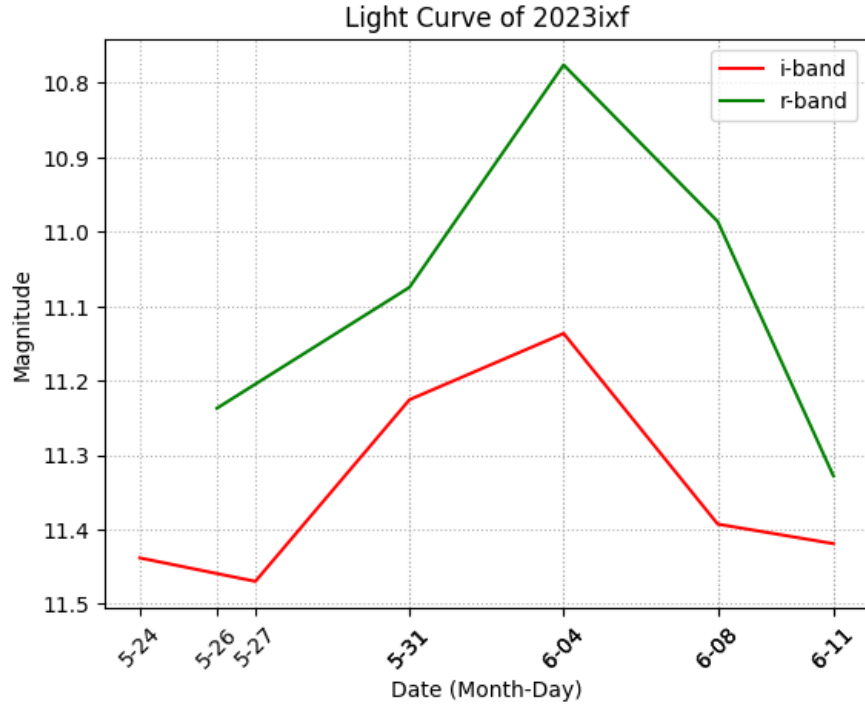


Figure 8: Light curve of 2023ixf for two bands

We see a peak for both bands around 6/4/2023. A comparison to data found by other scientists is done in the discussion.

4 Discussion

4.1 Classification

When starting this project, we were already warned that classifying supernovae would be difficult, if not impossible. This was mainly due to the fact that the filters available to us are fairly wide-banded. We were also unable to find reference stars for two of our observations. Due to this, we are unable to classify the unknown supernova.

Nevertheless, we are still able to see some differences that were expected. We know that type Ia supernovas typically exhibit a prominent peak in their light curves around 4000 angstroms, which falls within the visible spectrum (g-band). In contrast, Type II supernovae display a significant peak of around 7000 angstroms, located much deeper into the infrared region (i-band). We see that this is consistent with the first two supernovae in Table 3, where 2023ixf, the type II supernova has the largest magnitude in the i-band, whereas 2023foa, the type Ia supernova, has its largest magnitude in the g-band. These are both as expected.

4.2 Light Curve

We successfully created a light curve for 2023ixf over 2 bands, although only for a short period of time. This is mostly due to it not being discovered until much of the quarter had already passed. We still see a peak at around 6/4/2023. We can also find some light curves done by other scientists through the supernova database [6]. We find a curve by Yasuo Sano from the Nayoro Observatory [9]. While raw data is not available, we can see from a visual inspection that the peak of the curves happens around and most likely in between 5/31 and 6/4. This coarsely agrees with our light curve that finds the peak happening at 6/4 for both bands.

4.3 Reflection

After completing this project, there are two main things we would change.

1. Make sure reference stars are present in the FOV of the telescope before gathering

data.

2. Gather a lot more data!

The first was mostly a mistake on our part, we had naively believed at the time that reference stars are plenty in all parts of the sky, so we can just assume we will find some. As we now know, this is not the case. With this, we would probably have been able to provide some insight into the type of the unknown supernova. This would not have changed any of the work we had to do but would provide a nice conclusion.

The second was mostly out of our control. Due to the limited time of this class as well as the even more limited time on the telescopes, we are unable to gather significantly more data.

One of the things we would definitely not change regarding our work on this process is how we set up some Python code that can take in a fits file and automatically find reference stars and do all of the math for us. While this is not a difficult task, automating it saved a significant amount of time.

Overall, even with all the restrictions put on us from only having a ten-week class, we were able to produce not only a light curve but found photometry data for two supernovae that fit well with their given types.

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References

- [1] AoGoWo Cameron and JoWo Truran. “The supernova trigger for formation of the solar system”. In: *Icarus* 30.3 (1977), pp. 447–461.
- [2] J. B. Doggett and D. Branch. “A comparative study of supernova light curves.” In: 90 (Nov. 1985), pp. 2303–2311. DOI: 10.1086/113934.
- [3] G Israelian et al. “Evidence of a supernova origin for the black hole in the system GRO J1655-40”. In: *Nature* 401.6749 (1999), pp. 142–144.
- [4] Massimo Turatto. “Classification of supernovae”. In: *Supernovae and Gamma-Ray Bursters*. Springer, 2003, pp. 21–36.
- [5] Shinya Wanajo, Hans-Thomas Janka, and Bernhard Müller. “Electron-capture supernovae as the origin of elements beyond iron”. In: *The Astrophysical Journal Letters* 726.2 (2010), p. L15.
- [6] Avishay Gal-Yam et al. “Supernova discoveries 2010–2011: statistics and trends”. In: *Publications of the Astronomical Society of the Pacific* 125.929 (2013), p. 749.
- [7] Philip Lubin. “The search for directed intelligence”. In: *REACH* 1 (2016), pp. 20–45.

- [8] Larry Bradley. *astropy/photutils: 1.8.0*. Version 1.8.0. May 2023. DOI: 10.5281/zenodo.7946442. URL: <https://doi.org/10.5281/zenodo.7946442>.
- [9] Yasuo San. *2023ixf Light Curve*. 2023. URL: <https://www.flickr.com/photos/snimages/52960299217/>.