Color Photometry of the Type II-L Supernova 2023ixf

H. Markoff, I. Yip, and S. Soundappan

[1] Grafton Senior High School, Yale Summer Program in Astrophysics
e-mail: markoffhailey@gmail.com
[2] Houston County High School, Yale Summer Program in Astrophysics
e-mail: shivasoundappan2006@gmail.com
[3] Westlake High School, Yale Summer Program in Astrophysics
e-mail: ivysyip@gmail.com

August 4, 2023

ABSTRACT

Aims. To track the change in magnitude of 2023ixf over time and to determine its type.
Methods. The standard magnitude over time diagram for 2023ixf was composed based on fourteen nights of its observation. The photometric light curve of the supernova has been displayed relative to the time in days since its peak standard magnitude. The standard magnitude of the 2023ixf on a given day was found by calibrating its instrumental magnitude to the standard magnitude system. The resulting photometric light curve was compared to previously established photometric light curves for supernovae.
Results. 2023ixf is determined to be a Type II-L supernova.

Key words. photometric light curve – standard magnitude – type II-L supernova

[1]

1. Introduction

A supernova occurs when the gravitational potential energy of a massive star is greater than all other opposing forces, causing it to collapse. The resulting explosions can be broadly categorized into types Ia, Ib, Ic, and II supernovae. The type of supernova that is of interest in the study of 2023ixf is a type II supernova. It is one of the closest supernovae to the Milky Way Galaxy in decades; its host galaxy being Messier 101, commonly referred to as the Pinwheel Galaxy (Hiramatsu et al, 2023).

A type II supernova results from the core collapse of a massive star. The supernova will leave behind either a neutron star or a black hole. A type II supernova can be further classified into four types: type II-L, II-P, II-b, and II-n. The different classifications are useful in determining the evolution of a given star, which in turn can be used to create models to predict the way alternative stars will behave over time.

In studying the fluctuation in the standard magnitude of 2023ixf over time, the events preceding and succeeding supernova may be precisely determined, adding to the body of knowledge used to debate the precursors, longevity, and effects of type II-L supernovae.

Since supernovae are believed to be the sources of all elements heavier than iron present in the universe that are naturally occurring, their continual research is invaluable. In analyzing the behavior of type II-L supernovae, information is increasingly revealed about the nature of nuclear fusion in stars as well. Not only do type II-L supernovae illustrate the way stars will die, they produce shock waves that influence the formation of new stars. In studying the supernova 2023ixf, the patterns that future supernovae will follow have the potential to be observed with improved understanding. [2]

2. Methodology

All photometric data was obtained at the Leitner Family Observatory and Planetarium (LFOP) using 0.3m and 0.41m telescopes, the 0.43m Telescope 21 (Beryl Junction, Utah, USA) on iTelescope, and the 0.21m Telescope 5 (Beryl Junction, Utah, USA) on iTelescope.

Our supernova 2023ixf is in the galaxy Messier 101, the Pinwheel Galaxy. Since it is in a known galaxy, we pointed our telescope to the galaxy to collect photometric data on our galaxy. We often used the star Arcturus as our calibration star as it had a similar right ascension to our supernova and was easily recognizable. We took series of 60 seconds exposures on Sloan green and Sloan red filters on the telescopes at the LFOP, and used green and red filters for the iTelescope images.

We collected a total of 8 nights of usable data, 4 of which were acquired on the 0.41m telescope at LFOP, 2 on the 0.43m T21 telescope, and one on each the 0.3m and 0.21m telescopes respectively. We also had access to 6 images provided by Dr. Michael Faison taken on the 0.41m telescope before we began our research project, taken from 5/21/2023 to 6/29/2023.

MaximDL and AstroImageJ were used for the processing of the images. We median-combined sub-exposures for both the green and red filters each night. We calibrated each sub-exposure by subtracting the darks taken to eliminate hot pixels from the camera and to measure the CCD camera's response for the night. Most of the images were median-combined using the auto star alignment feature on MaximDL. However, we had encountered an issue with the files being too big for MaximDL for the night of

[1] Section written by H. Markoff

[2] Section written by H. Markoff

5/26/2023, which we resolved by using AstroImageJ to median-combine.

The standard magnitudes of calibration stars were obtained from the AAVSO Photometric All-Sky Survey (APASS) Data Release 9 database. We attempted to use the latest APASS Data Release 10 database, but encountered the issue that the region of the sky where the galaxy Messier 101 is located is not supported by the database. We picked 10 easily recognizable stars around the supernova of different magnitudes as our calibration stars and extracted their standard magnitudes in Sloan green and red filters. The right ascension, declination and standard magnitudes of the 10 calibration stars are below.

Right Ascension	Declination	Sloan-G	Sloan-R
14.067	54.305	13.677	13.319
14.073	54.323	12.176	11.779
14.046	54.370	15.682	15.182
14.053	54.397	15.772	15.252
14.047	54.370	13.89	13.384
14.048	54.275	14.159	13.518
14.042	54.282	14.465	13.816
14.060	54.438	15.11	14.582
14.054	54.458	15.282	14.719
14.063	54.447	15.876	15.573

Table 1. Standard Sloan Magnitudes of Calibration Stars

We collected the total amount of counts detected for each of those stars using AstroImageJ aperture selection, and transformed them into instrumental magnitudes using the instrumental magnitude equation (1).

i instrumental magnitude

b total number of counts

$$i = -2.5 \log(b) \tag{1}$$

We plotted the magnitudes of the calibration stars and found the coefficients for the transformation equations (Faison, 2009) for BVR photometry for each night using a least-squares fit program coded in python. We used (2) to fit the T_{vr} and C_{vr} constants and (3) to fit the T_V and C_V constants.

V standard sloan green magnitude

R standard sloan red magnitude

v instrumental green magnitude

r instrumental red magnitude

$$V - R = T_{\mathrm{vr}}(v - r) + C_{\mathrm{vr}} \tag{2}$$

$$V = v + T_V(V - R) + C_V \tag{3}$$

To find the slopes and y-intercepts of the least-squares fit lines, we used the following equation (Warrener, 2023).

N number of data points

x_i measured x values

y_i measured y values

b y-intercept of the least-squares fit line

m slope of the least-squares fit line

$$\begin{bmatrix} b \\ m \end{bmatrix} = \begin{bmatrix} N & \sum x_i \\ \sum x_i & \sum x_i^2 \end{bmatrix}^{-1} * \begin{bmatrix} \sum y_i \\ \sum x_i y_i \end{bmatrix} \tag{4}$$

After finding the transformation coefficients, we collected the total number of counts detected for our supernova using AstroImageJ. We used (1) to calculate the instrumental green and red values for each night, and used (2) and (3) with transformation coefficients found using the 10 calibration stars to calculate the color index and standard Sloan green magnitudes. We subtracted the results of (2) from that of (3) to also calculate the standard Sloan red magnitudes of our supernova. We also calculated the uncertainty of the magnitudes of the supernova due to uncertainty in the transformation equation line of best fit. We used the following equations to calculate the $\overline{\chi^2}$ for both transformation equation models.

N number of data points

x_i measured x values

y_i measured y values

n number of free variables

$$\chi^2 = \sum (y_i - f(x_i))^2 \tag{5}$$

$$\overline{\chi^2} = \sigma^2 = \frac{\chi^2}{N - n} \tag{6}$$

Since both lines influence the final standardized magnitude, the uncertainty in the magnitude is a combination of the uncertainty in both lines, which can be found using the following equation.

$$\sigma = \sqrt{\sigma_{\mathrm{vr}}^2 + \sigma_V^2} \tag{7}$$

After calibrating the supernova data to standard Sloan magnitudes, we plotted a standard magnitude versus time graph to model the change in magnitude of 2023ixf over time. We used light curve models of types Ia, Ib, II-b, II-L and II-P to determine the type of our supernova (Modjaz, 2019). We shifted the models horizontally and vertically in small intervals many times and found the $\overline{\chi^2}$ values to get the best fit for each model. We compared the lowest $\overline{\chi^2}$ values amongst the models to find the best model for our data to determine the supernova type of 2023ixf. We used the following χ^2 equation to account for the uncertainty in the data.

$$\chi^2 = \sum \frac{(y_i - f(x_i))^2}{\sigma^2} \tag{8}$$

[3]

[3] Section written by I. Yip

3. Results

After color-combining supernova images, the following Sloan-G and Sloan-R magnitudes were obtained for each of the 14 combined exposures, along with the following error values:

Julian Date	Telescope	Sloan-G	Sloan-R
2460086.59	0.41m	11.165 ±0.09	11.436 ±0.09
2460087.556	0.41m	10.915 ±0.09	11.294 ±0.09
2460091.635	0.41m	11.057 ±0.09	10.939 ±0.09
2460093.665	0.41m	11.061 ±0.09	10.953 ±0.09
2460094.603	0.41m	11.156 ±0.09	10.990 ±0.09
2460125.59	0.41m	12.080 ±0.09	11.599 ±0.09
2460141.757	0.43m	12.314 ±0.09	11.711 ±0.09
2460144.599	0.41m	12.704 ±0.09	11.995 ±0.09
2460144.796	0.43m	12.415 ±0.09	11.882 ±0.09
2460145.551	0.41m	12.841 ±0.09	12.324 ±0.09
2460152.63	0.3m	12.799 ±0.09	12.060 ±0.09
2460152.776	0.21m	13.230 ±0.09	12.156 ±0.09
2460158.621	0.41m	13.383 ±0.09	12.651 ±0.09
2460159.633	0.41m	13.312 ±0.09	12.721 ±0.09

Table 2. Standard Sloan Magnitudes with Uncertainties

After fitting each model [Ia, Ib, II-b, II-L, and II-P] to SN 2023ixf's Sloan-R magnitudes, the following $\overline{\chi^2}$ values were obtained:

Model	$\overline{\chi^2}$
Ia	25.640
Ib	1.903
II-b	1.401
II-L	1.045
II-P	7.923

Table 3. Lowest $\overline{\chi^2}$ values for each model for Sloan-R magnitudes

Since model II-L resulted in the lowest $\overline{\chi^2}$ value, the Sloan-R magnitudes supported that SN 2023ixf was type II-L. The model fit is seen in figure 1.

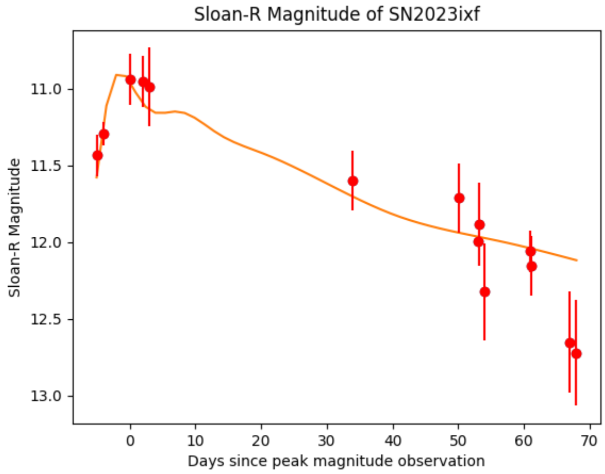

Fig. 1. The graph shows a type II-L supernova light curve (orange) fitted to SN 2023ixf Sloan-R magnitudes.

After fitting each model [Ia, Ib, II-b, II-L, and II-P] to SN 2023ixf's Sloan-G magnitudes, the following $\overline{\chi^2}$ values were obtained

Model	$\overline{\chi^2}$
Ia	36.068
Ib	2.246
II-b	17.707
II-L	26.783
II-P	103.608

Table 4. Lowest $\overline{\chi^2}$ values for each model for all Sloan-G magnitudes

Since model Ib resulted in the lowest $\overline{\chi^2}$ value, the Sloan-G magnitudes supported that supernova SN 2023ixf was type Ib. The best fit model is given in figure 2.

However, when looking only directly at the peak (first 5 data points), the following $\overline{\chi^2}$ values were obtained when fitting each model:

Model	$\overline{\chi^2}$
Ia	0.371
Ib	0.644
II-b	1.593
II-L	0.167
II-P	0.605

Table 5. Lowest $\overline{\chi^2}$ values for each model for first 5 Sloan-G magnitude points

Since model II-L resulted in the lowest $\overline{\chi^2}$ value, the Sloan-G magnitudes directly at the peak (first 5 data points) supported that SN 2023ixf was type II-L. The best fit model is shown in in figure 3.

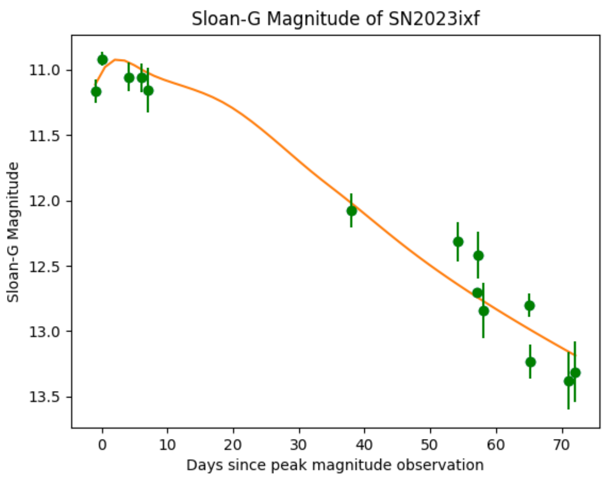

Fig. 2. Type Ib light curve (orange) fitted to SN 2023ixf Sloan-G magnitudes

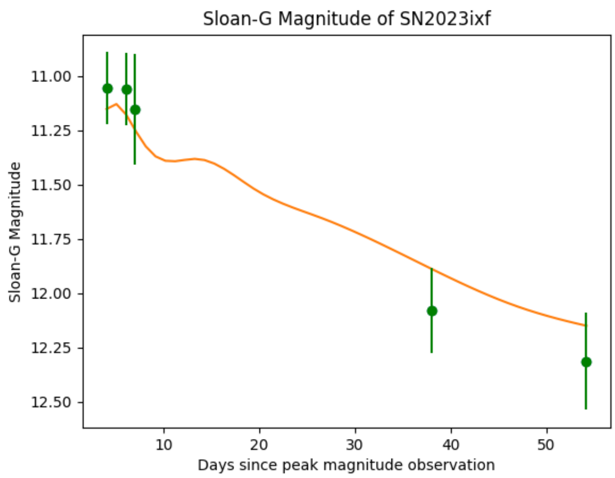

Fig. 4. Type II-L light curve (orange) fitted to SN2023ixf Sloan-G magnitudes immediately after peak

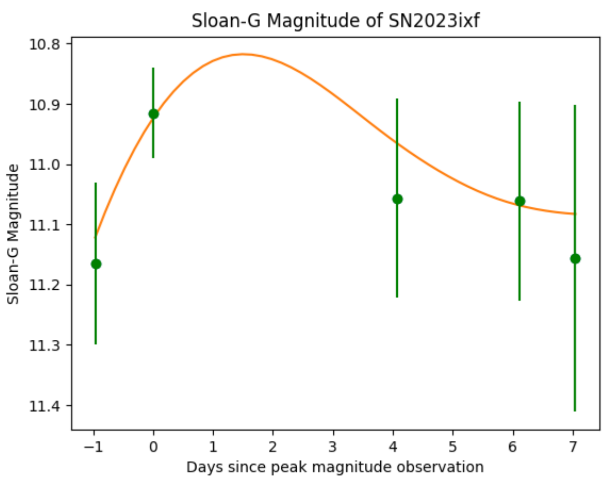

Fig. 3. Type II-L light curve (orange) fitted to SN 2023ixf Sloan-G magnitudes at peak

Similarly, when looking at only immediately after the peak (5/26/2023-7/15/2023), the following $\overline{\chi^2}$ values were obtained when fitting each model:

Model	$\overline{\chi^2}$
Ia	10.887
Ib	0.820
II-b	2.772
II-L	0.815
II-P	6.561

Table 6. Lowest $\overline{\chi^2}$ values for each model for Sloan-G magnitude points immediately after peak

Since model II-L resulted in the lowest $\overline{\chi^2}$ value, the Sloan-G magnitudes immediately after the peak also supported that supernova SN2023ixf was type II-L. [4]

4. Conclusion

Since the magnitudes at the peak and directly after the peak of a supernova light curve are most indicative of the supernova's type, we concluded that the Sloan-G magnitudes supported that SN 2023ixf was type II-L. It is probable that magnitudes measured near the end of the supernova light curve were less accurate due to the larger uncertainty values, and therefore they skewed the $\overline{\chi^2}$ values.

With both the Sloan-G and Sloan-R magnitudes supporting that SN 2023ixf was of type II-L, we conclude that SN 2023ixf is a type II-L supernova. This result agrees with results published in other papers (Yamanaka et al., 2023) (Sgro et al., 2023).

To further the research on SN 2023ixf, one can study the spectrometry of the supernova to also determine the type of supernova. Since the supernova is still bright, more observations can be done to further the light curve and validate the type of supernova. [5]

References

Faison, Michael (2009, September 26). Photometric Transformation Coefficients for CCD Filters.

Hiramatsu, Daichi & Tsuna, Daichi & Berger, Edo & Itagaki, Koichi & Goldberg, Jared & Gomez, Sebastián & De, Kishalay & Hosseinzadeh, Griffin & Bostroem, K. & Brown, Peter & Arcavi, Iair & Bieryla, Allyson & Blanchard, Peter & Esquerdo, Gilbert & Farah, Joseph & Howell, D. & Matsumoto, Tatsuya & McCully, Curtis & Newsome, Megan & Wheeler, J.. (2023). From Discovery to the First Month of the Type II Supernova 2023ixf: High and Variable Mass Loss in the Final Year Before Explosion.

Modjaz, Maryam, & Gutierrez, Claudia & Arcavi, Iair (2019, August 7). New regimes in the observation of Core-Collapse supernovae. arXiv.org. https://arxiv.org/abs/1908.02476

[4] Section written by S. Soundappan
[5] Section written by I. Yip

Sgro, Lauren & Esposito, Thomas & Blaclard, Guillaume & Gomez, Sebastian (2023). Photometry of Type II Supernova SN 2023ixf with a Worldwide Citizen Science Network.

Warrener, Michael (2023). Least Squares Regression Lab 2023.

Yamanaka, Masayuki & Fujii, Mitsugu & Nagayama, Takahiro (2023). Bright Type II SN 2023ixf in M101: A Quick Analysis of the Early-Stage Spectroscopic and Near-Infrared Light Curves.

Acknowledgements. Thank you to Yale University, the Yale Summer Program in Astrophysics, and the Leitner Family Planetarium and Observatory for hosting us this summer and allowing us to observe using their 0.3m and 0.41m telescopes. Thank you to Dr. Michael Faison, Mr. Michael Warrener, Mr. Tristan Weaver, Ms. Julia Levy, Mr. Tai Zheng, and Mr. Christopher Santiago for assisting us throughout our research process.