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Article

Photometric analysis of Type Ia Supernova 2023jvj

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SUMMARY
The study of supernovae – large explosions at the end of a star's life that release immense energy and various elements into space – is important in the fields of stellar evolution and the expansion of the universe. In the large cosmological time scale, supernovae allow for a short glimpse into the universe's evolution. Upon the discovery of Supernova (SN) 2023jvj, located in an anonymous galaxy in the Boötes constellation, our team launched an investigation to further knowledge of transient objects and their role in the cosmos. In this study, we conducted a photometric analysis of SN 2023jvj to determine its type and distance. We hypothesized SN 2023jvj would be a Type Ia supernova based on reports that there were no hydrogen spectral lines. We observed SN 2023jvj and collected photometric data over four weeks using the 12-inch Meade Schmidt Cassegrain Telescope (SCT) and 16-inch Ritchey-Chretien Telescope (RCT) at the Leitner Family Observatory and Planetarium (LFOP). Images were additionally collected remotely from Australia and Utah via the iTelescope Network. Using this data, standard Sloan green and Sloan red magnitudes were found through color calibration and used to generate a light curve (a plot of supernova brightness over time). SN 2023jvj was then determined to be a Type Ia supernova — a standard candle — with a distance modulus of 35.36. Therefore, SN 2023jvj is approximately 1.246e8 parsecs away from Earth. Our findings have a broader impact on how astronomers analyze the relationship between the brightness and distance of transient objects in the ever-expanding universe.

INTRODUCTION
A supernova is a stellar explosion that occurs at the end of the life of a white dwarf or massive star, releasing the majority of a star's mass. There are two main types of supernovae. Type Ia occurs when a white dwarf's mass exceeds the Chandrasekhar limit of 1.4 Solar Masses, the point at which a star collapses and implodes under its own weight, with no hydrogen lines in its spectra (1). As standard candles, they are useful in determining their distance from Earth based on apparent magnitude. Type IIp occurs when a star exhausts its hydrogen core, stopping helium fusion, and emitting hydrogen lines in its spectra (2). Due to this, pressure decreases, allowing gravity to overpower and force the star to collapse, forming a supernova.

The study of supernovae allows us to better understand stellar evolution and the interactions between different stellar bodies, therefore providing insight into the expansion of the universe as a whole (3). The study of supernovae helps with scientists' understanding of the evolution of stars as they implode and how they create other deep space objects such as black holes. They offer insight into the origins of the universe; as different elements are released form each supernova, they disperse throughout space to form planets and life. The short life of a supernova, however, can pose challenges in its research. On the event of poor weather, researchers could miss key details that occur during such rare events. Thus, it's important for astronomers to continue the study of supernovae (4).

Supernova (SN) 2023jvj was discovered on June 2, 2023 by the Zwicky Transient Facility and is located in an anonymous galaxy in the Boötes constellation (**Figure 1**).

We sought to analyze SN 2023jvj using aperture

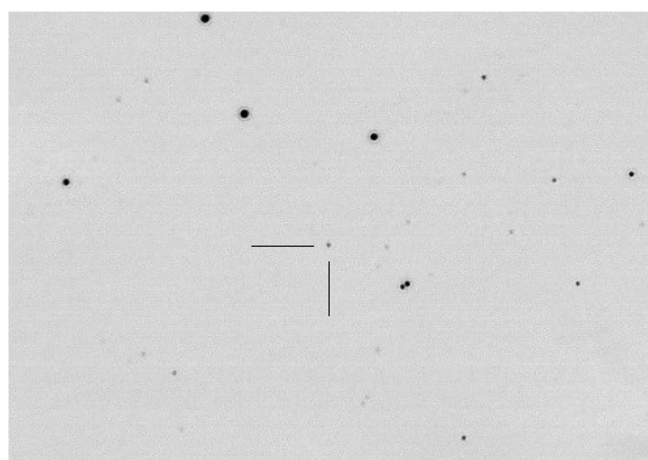

Figure 1: A Charge-Coupled Device (CCD) image of SN 2023jvj taken on the T17 telescope at Siding Springs Observatory through the iTelescope Network on July 13, 2023. The supernova is marked with a horizontal and vertical line and is located in an anonymous host galaxy.

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photometry, the process of summing each pixel's brightness value in a radius centered on an object and then subtracting the average pixel brightness of the surrounding night sky (5). For this analysis, we took images at the Leitner Family Observatory and Planetarium at Yale University and the iTelescope Network over the span of four weeks and determined the type and distance of the supernova. Reports in July of 2023 indicated that there were no hydrogen lines in SN 2023jvj's spectra, so we hypothesized that SN 2023jvj is a Type Ia supernova.

To test our theory, we calibrated our photometric data to a standard system of Sloan magnitudes (6). We fit our calibrated values to a standard light curve model of known supernovae to our experimental data, enabling us to determine the supernova's type, distance, peak magnitude, and date of peak magnitude.

Our conclusion was drawn based on light curve fitting and photometric analysis, proving there to be a decrease in brightness that matches the pattern of theoretical Type Ia supernovae models. As time continues, the brightness of SN 2023jvj is expected to decrease.

Through our work, we were able to confirm that SN 2023jvj is a Type Ia supernova located at approximately 1.246e8 parsecs away from Earth, with a peak magnitude of 15.921 on Modified Julian Day 60,121.6. Our findings will help to reinforce the validity of existing models of how distant supernovae light emissions change over time by providing more empirical data that align with aforementioned models.

RESULTS

We sought to analyze supernova 2023jvj to expand knowledge about transient objects in our universe, better understand stellar evolution, and interaction between celestial bodies. By using a generalized fit of chi-squared analysis for 10,000 different values of distance moduli and plotting a contour color map, we identified a best-fit estimate for the distance modulus of SN 2023jvj, which is a measure of distance of the supernova from Earth. The darkest area of the graph represents the lowest level of uncertainty and therefore the best distance modulus and x-shift of the data. In the standard supernova light curve models we used for analysis, the peak light emission occurs 1.95 days after day 0 of the model; therefore, the x-shift is how much we shift day zero of the model so that the model (with a peak 1.95 days after) fits best with the experimental data (**Figure 2**). Thus, the estimated value (from the darkest point on the contour plot) for the x-shift of the data was approximately 60,119 Modified Julian Days, and the estimated distance modulus was approximately 35. After, we more precisely calculated the chi-squared for a distance modulus value around 35 and an x-shift around 60,119 days using code and found that the best distance modulus was 35.36 ± 0.72 and the best x-shift was 60,119.6 Modified Julian Days. After adding the x-shift value to the initial 1.95 days, we found that the peak of SN 2023jvj occurred on 60,121.6 Modified Julian Day Number.

Using the difference between the apparent and standard magnitudes (the y-shift of the graph) we then calculated the distance of the supernova as being 12.5 ± 4.6 x 10^7 parsecs away from Earth.

To determine the supernova type, the apparent magnitude, or appeared brightness levels, of SN 2023jvj at each of the 7 observations (days in which we collected data) during the

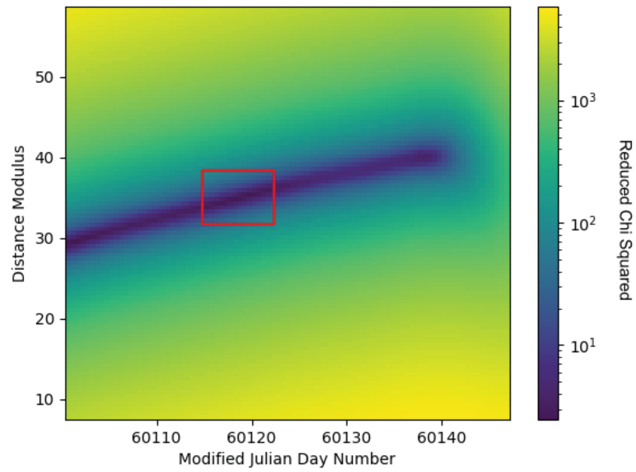

Figure 2: Estimation and Error of Distance Modulus of SN 2023jvj. This is a contour map of the distance modulus (a measure of how far away the supernova is) versus the Modified Julian Day Number of day zero on standard supernovae light curve models, with the Reduced Chi Squared error being represented by color. Using the calculated magnitudes for the data, chi-squared analyses were performed for all different potential values the distance modulus and Modified Julian Day Number, it is seen that the best-fit distance modulus (darkest area on the contour map), is approximately 35 with day zero (the x-shift) of the model being around 60,119 Modified Julian Days.

4-week period was then fitted to different standard light curve models of four supernova types (**Figure 3**). Through the fitted models, we determined that SN 2023jvj was a Type Ia supernova, since the data did not fit the models of Type II or Ib supernovae well, but it instead fit the Type Ia light curve model with the least amount of error (a chi-squared value of 0.72). The model allowed us to successfully conclude that SN 2023jvj is a Type Ia supernova.

To determine the peak magnitude of SN 2023jvj and the date in which the peak occurred, we fit Sloan-calibrated magnitudes of SN 2023jvj over the span of four weeks with a standard Type Ia light curve to the data (**Figure 4**). The downward trend in magnitude resembles the light curve of a typical Type Ia supernova, although several data points have large uncertainty values due to poor weather and light pollution in New Haven that obscured visibility and worsened clarity. The model indicates that SN 2023jvj peaked on the Modified Julian Date 60,121.6 (June 26, 2023) with corresponding Sloan green and Sloan red magnitudes of 16.212 and 15.631, respectively. The model suggests that the supernova will continue to dim at a roughly linear rate over the coming weeks.

DISCUSSION

Through our performed photometric analysis, we were able to plot the brightness of supernova SN 2023jvj over time; based on the light curve of SN 2023jvj, we determined that it is a Type Ia supernova with a distance modulus of 35.36 ± 0.72, located roughly 1.246 x 10^8 parsecs away from Earth. The calibrated green and red magnitudes gradually dim over time, showing that SN 2023jvj is moving past its peak brightness. However, due to the short total span of our observation time as well as our uncertainties, no substantial change in the color index values over time can be seen. Therefore,

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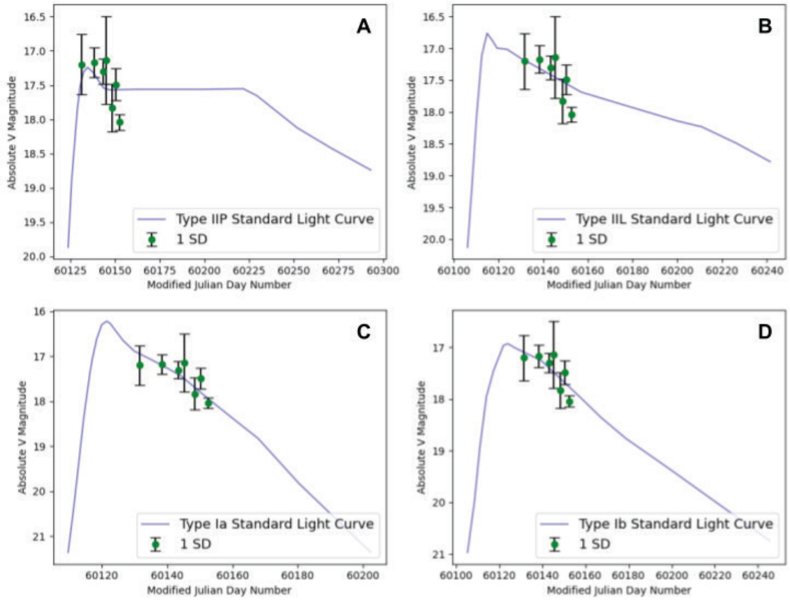

Figure 3: Observation data fitted to different standard light curves. The Sloan green apparent magnitudes of SN 2023jvj from each observation were fitted to four different supernovae standard models to determine the type of 2023jvj. The types include IIP (chi-squared value of 3.24) in graph A, IIL (chi-squared value of 2.34) in graph B, Ia (chi-squared value of 0.72) in graph C, and Ib (chi-squared value of 1.14) in graph D. It is seen that a Type Ia supernova fits best with the lease amount of error.

the fluctuations depicted are likely due to instrumental and observational errors and are not significant.

Type Ia supernovae tend to peak at SN 2023jvj's average luminosity of 15.921 because of the relatively fixed mass at which white dwarf stars explode (3). These supernovae are therefore useful for measuring Earth's distance from other galaxies based on their brightness. In this regard, the results of our study contribute to improving existing models of distant galaxies. By performing detailed photometric analysis on the brightness of SN 2023jvj over the course of a month, we contributed to the public information efforts of the American Association of Variable Star Observers database (AAVSO). Through our work, we have furthered developments in supernova research and understanding of their origins and behavior. Additionally, our studies of supernovae help our understanding of stellar evolution and the expansion of the universe as a whole by contributing to existing models of supernovae life and providing another data point on how far away various stars are. By comparing the absolute and apparent magnitudes of an observed object over time, as well as calculating its distance from Earth, scientists can use such relationships in changes in brightness to determine the speed in which the universe is expanding.

An increase in observation time, beginning from the supernova's initial explosion and spanning over several weeks, would strengthen current conclusions of the SN 2023jvj's type. To continue studying the behavior of SN 2023jvj, more green and red filter image data would be beneficial to further improve our models. In the future, we will develop automated methods for data processing and color calibrations in order to improve our models. New measurements of the supernova can also lead to a greater understanding of its composition and other physical properties.

Overall, our team's photometric studies on SN 2023jvj deepened our understanding of this supernova and others of its type. Through our research, our hypothesis that supernova

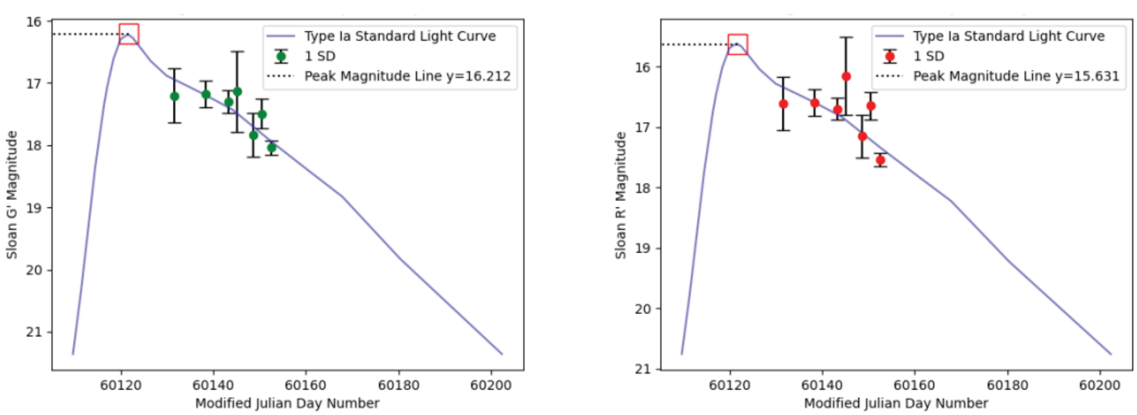

Figure 4: Standard Sloan green and Sloan red magnitude of SN 2023jvj fitted to a Type Ia light curve. The standard magnitudes of our observations are plotted against Julian days. They are then shifted to fit the standard light curve of a Type Ia supernova.

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2023jvj was a type Ia supernova was supported by our findings, and so our data will contribute to the knowledge and research on Type Ia supernovae. Through our observations, we were able to increase the understanding of supernova classification as well as photometric analysis of transient celestial objects; the process and methods we use to calculate the type and distance modulus of the supernova will help future researchers in the field to more easily perform photometric analyses on other celestial bodies. By finding the type, distance modulus, magnitude, and date of peak magnitude of SN 2023jvj, we gained deeper insight into the nature of Type Ia supernovae and other transient objects, the physics behind stellar evolution, and the expansion of our universe.

MATERIALS AND METHODS

Observations

Over a four-week period, images of SN 2023jvj were taken using an (f/6.3) 12-inch Meade Schmidt Cassegrain Telescope with a SBIG STT1603ME CCD camera and a (f/8.9) 16-inch Ritchey-Chretien Telescope with an ASI2600MM Pro CMOS camera. With a right ascension of 13h 53m 02s and a declination of +16°49'11'', SN 2023jvj transited at approximately 20:00 EDT. Charge-Coupled Device (CCD) images were taken between 21:00 EDT and 23:30 EDT to maximize the altitude of the supernova. To calibrate the telescopes, we used the application TheSkyX Pro, to direct the instrument towards a calibration star, Arcturus, and ensure the telescope was focused. Once in focus, we slewed the telescope to the J2000 coordinates of SN 2023jvj (7). We took a series of images in the Sloan green and Sloan red filters with 1x1 binning to maximize the number of photons collected and exposure times ranging from 45 to 60 seconds to improve the signal-to-noise ratio.

Additionally, we took images remotely through the iTelescope Network using the 17-inch Planewave Corrected Dall-Kirkham (CDK) Telescope (T17) at Siding Springs Observatory in Coonabarabran, Australia, and the 20-inch Planewave CDK Telescope (T11) at Utah Desert Remote Observatory. All of these images were 120-second exposures taken with 1x1 binning in Sloan green and Sloan red filters.

By the end of the observation period using telescopes from the Leitner Family Observatory and Planetarium and iTelescope, we had collected 7 days of measurable data (**Table 1**). Dates were chosen with a few days in between so that changes were more prominent and so we could observe a larger portion of the supernovae's life, but telescope availability at the Leitner Family Observatory and Planetarium and through the iTelescope network was also a contributing factor.

Photometric Analysis

To perform a photometric analysis on SN 2023jvj, we calibrated the supernova against standard stars to find the magnitude and calculate the chi-squared value of uncertainty. Through computer astronomy software, such as MaximDL and AstroImageJ, and transformation equations, we calibrated our images to find the apparent magnitude of SN 2023jvj relative to its surrounding stars in a process known as aperture photometry. Consequently, we were able to reach our goal of finding the supernova's type by plotting a light curve of its magnitude over time and calculating the distance

Date	Telescope	Filter	Exposure Time (sec)
07/06/23	12-inch	Sloan-r	15x60
07/13/23	T17	Sloan-g	15x120
		Sloan-r	15x120
07/18/23	T17	Sloan-g	15x120
		Sloan-r	15x120
07/19/23	T11	Sloan-g	3x120
		Sloan-r	6x120
07/22/23	12-inch	Sloan-g	5x60
		Sloan-r	9x60
07/25/23	T17	Sloan-g	15x60
		Sloan-r	15x60
07/26/23	16-inch	Sloan-g	11x45
		Sloan-r	7x45

Table 1: Measurable Observations collected over the 4-week period. The table provides information about each observation, including the date, telescope model, filter, and exposure time (number of images x seconds).

modulus.

After collecting our data, we used the software Maxim DL to process the measurable images for each date by implementing dark frame subtraction and image alignment through automatic star-matching. We then median-combined images that were taken through the same filter.

After using the plate-solving function available through the website Astrometry.net, we identified 20 calibration stars from both Sloan green and Sloan red median-combined images. These stars helped us standardize all of our data. Additionally, we created star finder charts for these calibration stars (**Figure 5**). The standard Sloan green and Sloan red magnitudes of these stars were determined using APASS data by matching the right ascension and declination of SN 2023jvj and the field of view of the telescope with the largest diameter – the T11 telescope in Utah. With these standard

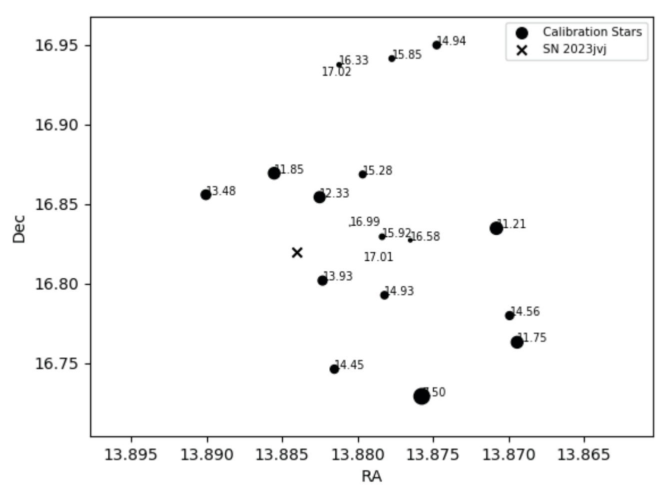

Figure 5: Standard magnitudes of Sloan green calibration stars at their corresponding Right Ascension (RA) and Declination (Dec), taken from the AAVSO Photometric All-Sky Survey. The dots represent calibration stars surrounding the supernova labeled by their magnitudes, and "X" marks the location of SN 2023jvj.

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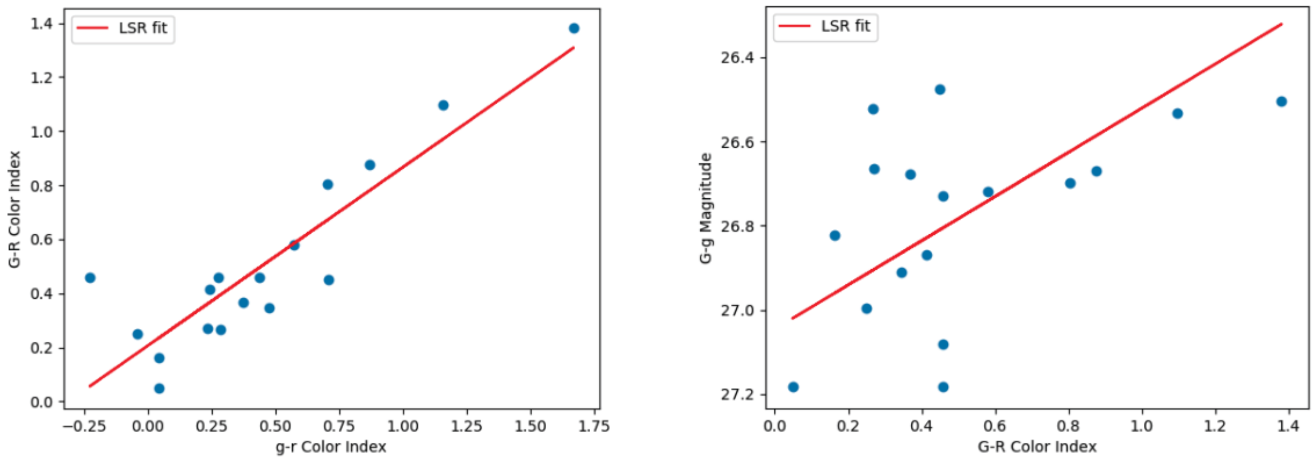

Figure 6: G - g vs. G - R of APASS calibration stars. These are images taken on 07/25/2023, fit to a linear function. The red line depicts the least-squares regression (LSR) line of the uncalibrated magnitude, obtained from performing photometric analysis of SN 2023jvj, subtracted from the calibrated magnitude, obtained from measuring the brightness of stars with known magnitudes, versus the uncalibrated color index in the left graph. In the right, the LSR line depicts the relationship between the difference in the calibrated and uncalibrated green magnitude versus the calibrated color index. The slopes and the y-intercepts of these lines are the transformation coefficients in **Table 2**.

magnitudes, we were able to apply standard transformation equations of the Sloan green and Sloan red filters to determine the photometric calibration of our supernova.

In the equations below, *v* (green) and *r* (red) are instrumental magnitudes, *V* (green) and *R* (red) are standard magnitudes, and T_{vr}, C_{vr}, T_V, and C_V are the transformation coefficients. We calibrated each image using the flux of the calibration stars with the following transformation equations:

$$V - R = T_{vr}(v-r) + C_{vr}$$

$$V = v + T_V(V - R) + C_v$$

Through linear transformations and color calibrations, we were able to standardize all the values to the Sloan system. We graphed *G - R* vs. *g - r* as well as *G - g* vs. *G - R* using the calibration star data to find the correlation between instrumental magnitudes and standard Sloan magnitudes. Through least-squares regression line (LSRL) fitting, we solved for the best-fit slope (*T*) and y-intercept (*C*) in order to calibrate each night of data (8).

We calculated *G - R*, or the color index, of SN 2023jvj using transformation coefficients (**Table 2**). Additionally,

Date	T_{vr}	C_{vr}	T_V	C_V
07/06/23	N/A	N/A	N/A	N/A
07/13/23	0.861	0.082	-0.201	27.066
07/18/23	0.927	-0.037	0.138	26.474
07/19/23	0.469	0.691	-0.325	26.858
07/22/23	-0.035	0.620	2.260	24.123
07/25/23	0.663	0.206	-0.526	27.047
07/26/23	0.818	0.340	-0.327	26.910

Table 2: Best-fit slopes (T) and y-intercepts (C) for each observation date. This was calculated using transformation equations.

these coefficients were used to calculate the standard Sloan green and Sloan red magnitudes of the supernova in order to generate a light curve.

However, on July 6, 2023, images were taken in only the red filter. Given that there were no images in the green filter, we could not perform color correction on the color index to yield the magnitude of SN 2023jvj. Therefore, we only calculated the instrumental to standard offset. We solved for the instrumental red magnitudes of the calibration stars and compared them to APASS standard green and red magnitudes. We found the average difference between the instrumental red and standard red, as well as the average difference between the instrumental red and the standard green values of the calibration stars. These average differences (25.36 for G-r and 24.73 for R-r) were added to the supernova's instrumental magnitude to obtain standard values. However, this method results in higher uncertainty values and greater potential error.

To calculate the error and the goodness of fit of the data points, one can use chi-squared analysis (9) to determine the root mean square (RMS) value (10):

$$\chi^2 = \sum(y_i - f(x_i))^2 / \sigma^2$$

where y_i is the predicted value and $f(x_i)$ is the calibrated data. Using the chi-squared value of uncertainty, one can also find the level of variance and therefore the RMS:

$$V = \sigma^2 = \chi^2 / (N - n)$$

where *N* is the number of data points and *n* is the degree of freedom.

Using the T_{vr}, and C_{vr}, values from least-square regressions, we were able to solve for chi-squared and the RMS with 2 degrees of freedom. Our line of best fit minimizes chi-squared (**Figure 6**).

Distance Modulus

To find the distance from the Earth to the supernova, one can use the distance modulus equation, which is defined by the following formula:

$$m - M = -5 + 5 * \log(D)$$

where m is the apparent magnitude and M is the absolute magnitude. Solving for D, the distance in parsecs,

$$(m - M + 5)/5 = (35.36 \pm 0.72 + 5)/5 = \log(D)$$

Therefore, the distance of SN 2023jvj is $12.5 \pm 4.6 \times 10^7$ parsecs away from Earth.

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