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Article

Sloan green and red photometry of the Type Ia supernova 2024neh

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SUMMARY

Supernovae play a key role in understanding stellar evolution and cosmic distances. Type Ia supernovae, the thermonuclear explosions of white dwarfs in binary systems, can help measure the expansion of the universe. Type Ia supernovae can be classified by their light curve, which displays a rapid rise to peak magnitude followed by a gradual decline. Based on observations conducted at the Sierra Remote Observatory and the Leitner Family Observatory and Planetarium, we present an early analysis of extragalactic supernova (SN) 2024neh. The Zwicky Transient Facility (ZTF) discovered SN 2024neh on June 30th, 2024, with a discovery magnitude of 19.4398 in the Sloan green (g) filter. Based on this information, we hypothesized that SN 2024neh is a Type Ia supernova. To test this hypothesis, we conducted aperture photometry on our time series data in the Sloan g and Sloan red (r) bands. Then, we applied least squares linear regression and chi-squared minimization on the Julian day and distance modulus to analyze the apparent magnitude of SN 2024neh. Additionally, we used model fitting on the light curve to estimate the date of peak magnitude of SN 2024neh to be Julian Date 2460510.5 and report an estimated distance modulus of 35.7 ± 0.1466 in the Sloan g filter. We calculated that SN 2024neh was 138 ± 9.319 megaparsecs (Mpc) from Earth. Since this distance is farther than its host galaxy UGC 9696, which is approximately 107.23 Mpc from Earth, we conclude that SN 2024neh is located in the background of its galaxy. Through model fitting, the light curve shape is consistent with that of a Type Ia supernova, so our findings support SN 2024neh being a Type Ia supernova. Our findings contribute to the broader catalog of Type Ia supernovae, supporting the development of more accurate supernova evolution models, a critical tool in measuring cosmic expansion.

INTRODUCTION

Stars evolve for over millions and billions of years, undergoing dramatic changes over their life cycles. While smaller stars, like the Sun, will gradually shed their outer layers and leave behind dense cores, known as white dwarfs, more massive stars end their life cycles in explosions called supernovae, which release an immense amount of energy and disperse heavy elements into space (1). There are several supernova types, which occur under different circumstances. The primary distinctions between supernova types are found within their spectra, graphs that plot the intensity of light at different wavelengths. Type I supernovae lack hydrogen in their spectra, while Type II supernovae exhibit hydrogen lines (2).

Another way to distinguish between these types is by analyzing their light curves, which measure a supernova's high luminosity over time. Since different types of supernovae are triggered by different events – such as the thermonuclear explosion of a white dwarf in Type Ia supernovae or the core collapse of a massive star in Type Ib and Type II supernovae – they exhibit distinct patterns in their light curves (2). Type Ia supernovae (SNe Ia) typically display a rapid initial increase in luminosity followed by a gradual decline in brightness over a period of a few months. Type Ib exhibits a similar shape but with a slower decline, Type IIb rises quickly and often shows a second peak, Type IIP shows a plateau after the initial peak, and Type IIL declines more linearly (2).

One subclass of Type I supernovae, Type Ia supernovae (SNe Ia), originates from two known scenarios involving at least one white dwarf in a binary star systems. The first scenario occurs when a white dwarf and a companion star, most likely a red giant, are in proximity. The white dwarf will pull the red giant towards itself due to its density being far greater than that of the red giant, causing the white dwarf to accrete mass from the red giant (3). The white dwarf star remains stable because its electron degeneracy pressure counteracts the inward force of gravity, preventing collapse (4). However, when the white dwarf's accumulated mass approaches the Chandrasekhar limit of ~1.4 $M_\odot$, the gravitational force exceeds the degeneracy pressure, leading to a collapse that culminates in a supernova (5). In the double degenerate scenario, the binary system consists of two white dwarfs. These stars will gradually spiral toward each other and eventually collide and merge due to gravitational effects, resulting in instability and triggering a supernova explosion due to their combined, extremely high density (6). In either case, a tremendous amount of energy is released across the electromagnetic spectrum.

Type Ia supernovae are particularly important in astrophysics because of their highly predictable luminosity evolution, making them valuable as "standard candles" for measuring cosmic distances (7). This predictability is because all white dwarfs collapse at nearly the same critical mass, meaning all SNe Ia reach a similar peak brightness (absolute magnitude of around -18.65 ± 0.6 when it's located 10 parsecs away, or approximately 3 billion times the brightness of the Sun) (8). By comparing their known brightness to how bright they appear from Earth, their distance from Earth can be calculated. This ability to measure cosmic distances has been crucial in major discoveries, such as proving that the universe is expanding at an accelerating rate due to dark energy (9). With precision reaching better than 6% after applying corrections accounting for variations in light curve shape and color, SNe Ia provide one of the most reliable empirical methods for measuring distances across such scales (10).

In our study, we examined SN 2024neh. Its host galaxy, UGC 9696, is located approximately 107.23 Mpc away from the Earth (11). This distance was estimated using redshift, a method that calculates distance from Earth by determining how fast the galaxy is moving away from it based on the concept that a galaxy's light stretches to longer wavelengths as the universe expands (12).

Based on SN 2024neh's recent formation and its low discovery magnitude of 19.4398 in the Sloan green (g) filter relative to other supernovae, we hypothesized that SN 2024neh was a Type Ia supernova (13). To test our hypothesis, we analyzed distinct patterns through plotting light curves and using chi-squared minimization to determine key parameters, such as the supernova's type, peak brightness date, and distance. By applying this method in our research, we discovered that SN 2024neh's light curve profile and color evolution in the Sloan g and red (r) bands corresponded with existing data on confirmed SNe Ia, thereby supporting its classification as a Type Ia supernova and our initial hypothesis.

RESULTS

Light Curve

To address the gap in classifying SN 2024neh and determining its physical properties, we hypothesized that it was a Type Ia supernova based on its discovery magnitude. First, we analyzed its brightness over time by creating light curves. We utilized the calculated standard Sloan g and Sloan r magnitudes and errors to create the light curve of SN 2024neh (**Table 1**). Then, we plotted the magnitude versus Julian day for both Sloan g and r filters (**Figure 1**). For both Sloan g and r light curves, the linear regression line fitted to the data is sloping downward, indicating SN 2024neh is dimming over the period it was observed.

Next, the r-value, or correlation coefficient, was calculated. The r-value measures the strength and direction of the linear relationship for the data points plotted. This equation was used, where Cov(X,Y) is the covariance between the observed and predicted data, and σ_X and σY are their standard deviations:

$$r = \frac{Cov(X,Y)}{\sigma_X \sigma_Y} \qquad \text{(Equation 1)}$$

A line of best fit was plotted to each light curve (**Figure 1**). These lines of best fit yielded an r-value of 0.85 and 0.62 for green and red magnitudes, respectively (Equation 1). 0.85 signifies a strong positive correlation for the green magnitude and 0.62 indicating a moderate positive correlation for the red magnitude. This suggests that the light curve in the green band has a more consistent trend than the red band, potentially because of differences in the supernova's evolution at different wavelengths.

Next, we fit the Sloan g light curve to various model light curves including Type Ia, Ib, IIb, IIL, and IIP (**Figure 2**). Then, we calculated the chi-squared values for each light curve model, where smaller values indicate a better fit (**Table 2**). The Type Ia light curve, with the smallest chi-squared value of 14.07, provided the best fit for SN 2024neh, compared to values of 20.97 (Ib), 15.69 (IIb), 23.74 (IIL), and 26.17 (IIP). The corresponding p-value was approximately 0.015, suggesting the Type Ia curve provides a statistically significant fit.

Knowing that the Type Ia light curve is the best fit, we were able to approximate the peak magnitude date of SN 2024neh. According to the Type Ia model, our first data point's date is shortly after the peak magnitude date (**Figure 2**). Therefore, the peak magnitude date is estimated to be around 2460510.5.

Using chi-squared minimization, we found the shift in the y-axis that optimizes the fit of the Type Ia light curve to SN 2024neh's light curve. This shift then corresponds to the distance modulus of the Sloan g filters, and the error was estimated using the 1σ contour line (**Figure 2**). The resulting distance modulus is 35.7 ± 0.1466. Utilizing the logarithmic relation between distance modulus and distance, this corresponds to a calculated distance from Earth of 138 ± 9.319 Mpc.

Julian Date	G(Mag)	R (Mag)	Error (G)	Error (R)	Air mass	Telescope
2460511.5	15.83696156	15.81202002	0.322164459975708	0.4685460805	2.23	T24
2460512.5	16.65882429	16.22088021	0.19141808628808	0.2940468425	1.64	T24
2460516.5	16.69244027	16.28025849	0.205933793748523	0.2615115348	1.75	LFOP 0.4m
2460517.5	16.96671544	16.58111945	0.190981782492297	0.3023155229	1.47	LFOP 0.4m
2460518.5	17.49276618	17.09564919	0.216698040383317	0.3151671587	1.40	LFOP 0.4m
2460520.5	18.07831592	18.10849116	0.440676619518531	0.552308696	1.45	LFOP 0.4m
2460522.5	17.39501035	16.43101399	0.153760185440222	0.2378416381	1.39	LFOP 0.4m

Table 1: Measurements of SN 2024neh over 12 days. The table shows the observed magnitudes in the Sloan g and r filters, along with errors, air mass, and the telescopes used for each Julian Date.

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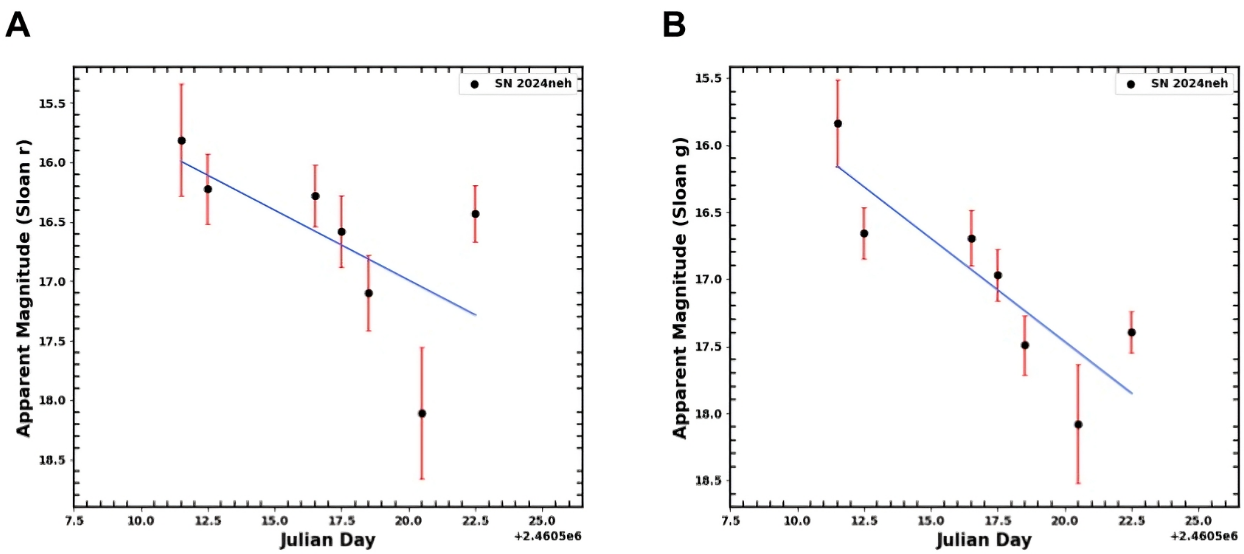

Figure 1: SN 2024neh light curve in Sloan green (g) and red (r) bands. (A) A line of best fit is plotted for the data in the Sloan g band. The downward trend in this linear regression line indicates that SN 2024neh has been dimming since the peak measurement. (B) A similar line of best fit is plotted for the data in the Sloan r band, also with a downward linear regression line. The vertical error bars represent the uncertainties in the apparent magnitude measurements.

Color Evolution

To further evaluate our hypothesis that SN 2024neh is a Type Ia supernova, we used its (g-r) color index to see how its color changed over time. Type Ia supernovae typically become redder as they cool after peak brightness (14).

In the color evolution plot, the least squares linear regression line has a positive slope and upward trend in its (g-r) color index (**Figure 3**). This indicates that SN 2024neh is cooling down and reddening over time. SN 2024neh's color cannot be determined for Julian days 2460511.5 and 2460520.5 due to the error bars reaching both positive and negative values. However, for the other days observed, SN 2024neh's color is tinted red. This line produced an r-value of 0.44, which suggests a somewhat weak positive correlation with some scatter in the color evolution trend.

DISCUSSION

We hypothesized that SN 2024neh was a Type Ia supernova. To test this hypothesis, we performed aperture photometry, compared the resulting Sloan g and r light curves with five standard supernova light curves, and examined the color evolution of SN 2024neh. We determined three key pieces of information about SN 2024neh by fitting our light curve to standard models of five different types of supernovae. We determined that SN 2024neh is a Type Ia supernova, it reached its peak magnitude around Julian Date 2460510.5, and it is approximately 138 ± 9.319 Mpc away from Earth.

We compared our calculated distance of SN 2024neh from Earth, 138 ± 9.319 Mpc, to the distance of its host galaxy, UGC 9696, which is approximately 107.23 Mpc away from the Earth (11). The lower bound of our calculated distance, accounting for the uncertainty, is 128.681 Mpc. The distance of the galaxy is around 3.3σ away from this lower bound, which exceeds the typical 3σ threshold for statistical significance, meaning there is 0.3% probability of the difference to have occurred from chance (15). Therefore, we suggest that SN 2024neh is likely not physically associated with its galaxy but instead located in the background. This highlights the importance of verifying a supernova's host galaxy in future observations to avoid inaccurate redshift or distance estimates.

The Type Ia model produced the best fit with the lowest chi-squared value of 14.07. In addition, the color evolution in the (g-r) color index showed cooling and reddening, indicating that SN 2024neh is most likely a Type Ia supernova. The models Ib, IIL, and IIP showed significantly poorer fits with higher chi-squared values. However, we found that the Type IIb light curve also fits reasonably well, with a chi-squared value of 15.69. This suggests that a Type IIb classification could also be a possibility. If it was Type IIb, its underlying explosion mechanism would differ significantly because the massive stars they originate from have not lost all of their hydrogen envelopes prior to explosion (16). As a result, their early light curves can resemble those of Type Ia supernovae, but they exhibit a more prolonged cooling phase due to residual hydrogen interacting with the expanding ejecta (2). This distinction is important because unlike SNe Ia, which were previously mentioned as standard candles due to their uniform peak luminosity, Type IIb supernovae are

Filter	Ia	Ib	IIb	IIL	IIP
g	14.06908	20.9727	15.6917	23.7443	26.1714

Table 2: Chi-squared values for supernova light curve model fitting to Sloan g filter. The Type Ia model gave the smallest chi-squared value, indicating it is the best-fitting model.

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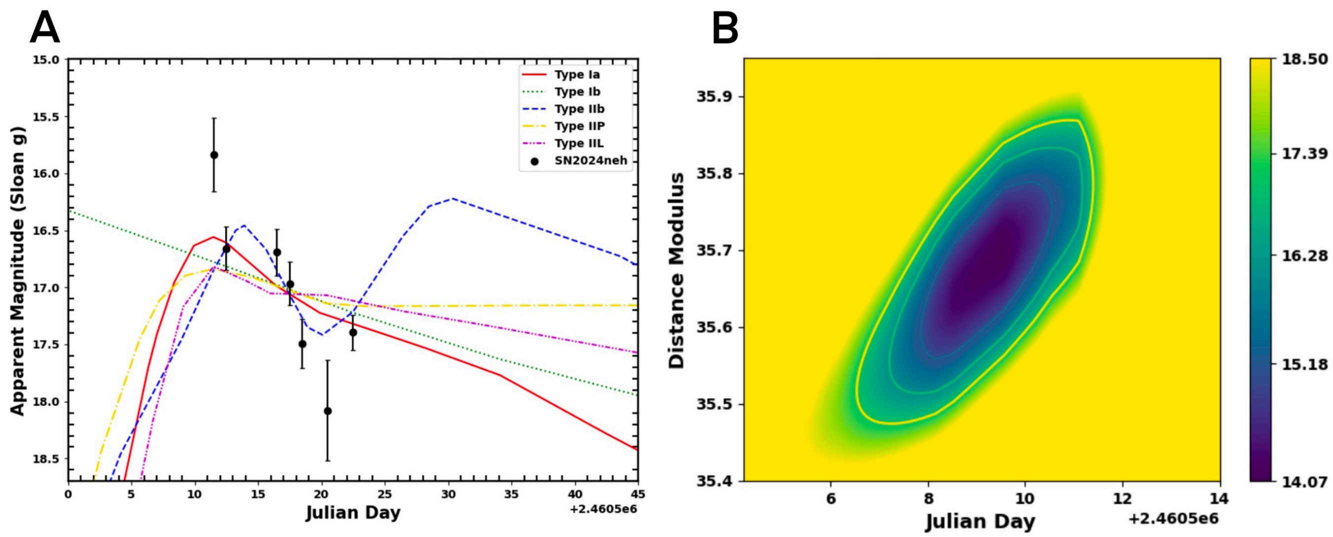

Figure 2: SN 2024neh light curve model fitting and chi-squared heatmap (in Sloan g). (A) The light curve model fitting for Type Ia, Ib, IIb, IIP, and IIL supernovae models, with Type Ia providing the best fit to our data. (B) The chi-squared heatmap for the Type Ia supernova model, which indicates the uncertainty in our estimated distance modulus.

more heterogeneous in brightness and are less useful for cosmological distance measurements (17).

To verify this classification, we examined spectra. Although we were unable to obtain spectra ourselves due to SN 2024neh being too faint for our equipment, the Zwicky Transient Facility (ZTF) group published spectra for SN 2024neh on the Transient Name Server (13). The spectra show prominent silicon II (Si II) absorption lines and minimal hydrogen absorption lines. Si II is one of the most distinguishing features of SNe Ia, and SNe Ia lack the hydrogen absorption lines that are prominent in Type IIb supernovae (2). Thus, these spectra further support the classification that SN 2024neh is likely a Type Ia supernova.

The similarity between the fits of the Type Ia and Type IIb models to our data makes SN 2024neh an intriguing supernova. Additional data points and spectra would help us confirm this classification and could provide valuable insights into distinguishing between these types, helping astronomers more accurately classify Type Ia and Type IIb supernovae in the future. Furthermore, obtaining more detailed or higher-resolution spectra of SN 2024neh would be valuable in determining the velocity of the supernova ejecta as well as the redshift (18). This information would not only refine our understanding of SN 2024neh but could also help determine the movement of its host galaxy and contribute to improving models of supernova evolution, which play a key role in studies of our universe's expansion (19).

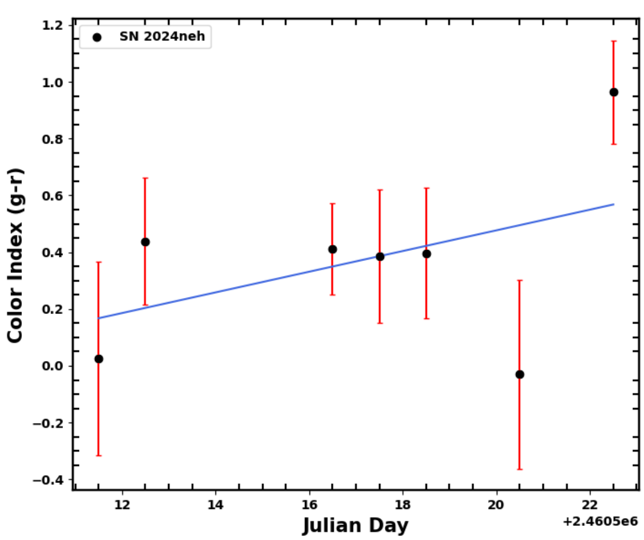

Figure 3: Standard g - standard r magnitudes against Julian day. The upward trend in the linear regression line suggests that SN 2024neh is becoming redder and cooling down over the observed time.

MATERIALS AND METHODS

Photometry

J2000 coordinates for SN 2024neh were obtained from the Rochester Astronomy Database, with a Right Ascension (RA) of 15h05m31.32s and Declination (Dec) of +08°31'51.60" (20). SN 2024neh was first discovered on June 30, 2024, at 06:49 UTC by the Zwicky Transient Facility (ZTF), and is located in the host galaxy UGC 9696 (13). Observations of SN 2024neh began on Julian Day 2460500.5. Images of SN 2024neh were captured using two telescopes: a 0.4 m, f/8.9 focal ratio, 123.75 x 82.50 arcminute field of view telescope at the Leitner Family Observatory and Planetarium (LFOP) in New Haven, Connecticut, and a 0.61 m, f/6.5 focal ratio, 31.8 x 31.8 arcminute field of view T24 telescope at the Sierra Remote Observatory in Auberry, California.

During each observation session, images with 60-second exposure times were captured using Sloan g (central wavelength of 4770 ˚A), Sloan r (central wavelength of 6231˚A), and dark calibration frames. These images were then processed using Siril 1.2.01, with the green and red images being dark subtracted and median combined.

Next, the sky-subtracted flux of 20 standard stars surrounding SN 2024neh was measured using AstroImageJ (**Figure 4**). The same method was used to find the flux values for SN 2024neh. Regarding the photometry process, a three-ring aperture was placed on each standard star, and the

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Number	RA (J2000, degrees)	DEC (J2000, degrees)	G (Mag)	R (Mag)
1	226.2333	8.5594	9.637	8.211
2	226.2667	8.4378	14.562	13.265
3	226.1702	8.3676	15.696	15.437
4	226.2458	8.4203	15.841	15.39
5	226.1958	8.4281	17.215	16.676
6	226.2499	8.3579	12.771	12.428
7	226.3071	8.6201	14.511	13.897
8	226.3792	8.4611	13.063	12.462
9	226.3542	8.4686	16.424	15.796
10	226.3833	8.5667	13.710	12.982
11	226.3125	8.5867	11.755	11.399
12	226.2828	8.4785	16.576	15.742
13	226.3392	8.5318	15.629	15.295
14	226.3500	8.3761	14.978	14.618
15	226.3583	8.3778	16.017	15.189
16	226.3912	8.4637	16.502	16.077
17	226.5208	8.4856	11.724	10.861
18	226.5125	8.4719	15.990	14.843
19	226.2292	8.5303	13.339	12.898
20	226.3556	8.4333	16.237	15.782

Table 3: Measurements for 20 standard stars based on APASS. The right ascension (RA) and declination (Dec) of 20 standard stars are listed with their Sloan g and r magnitudes, used to conduct photometry for SN 2024neh.

flux in the first ring was measured. Then, the outer ring of the aperture (the average background noise) was subtracted from the flux. This resulted in the sky-subtracted flux, which we then used to calculate the instrumental magnitudes with the following equation:

$$m = -2.5 \log b \qquad \text{(Equation 2)}$$

where m is the instrumental magnitude and b is the sky-subtracted flux.

The standard green and red magnitudes of these stars were obtained from the AAVSO Photometric All-Sky Survey (APASS) Data Release 10 (21) (**Table 3**).

With both instrumental and standard calibration star magnitudes in the green and red filters, a least squares linear regression model fitting was applied to the color index and green magnitude data. This was done to solve for the color offsets, Tgr and Cgr, as well as the green magnitude offsets, Tg and Cg. The equation used is the photometric transformation equation for the g and r filters (22). Std represents standard magnitudes, and Inst represents instrumental magnitudes:

$$Std(g-r) = T_{gr} \cdot Inst(g-r) + C_{gr} \qquad \text{(Equation 3)}$$

$$Std(g) - Inst(g) = T_g \cdot Std(g-r) + C_g \qquad \text{(Equation 4)}$$

The standard magnitudes of SN 2024neh in the Sloan g and

Julian Date	T_{gr}	C_{gr}	T_g	C_g
2460511.5	0.0456185287030102	0.657679831407674	0.477526619139098	22.9360624729075
2460512.5	0.998343419423616	0.528395890653157	0.16191404703278	24.2926806642956
2460516.5	0.968309618717823	0.470916859281357	-0.0953292928867028	24.7619594652366
2460517.5	0.731659264385022	0.487604841280145	0.107073596899738	25.0281924851841
2460518.5	0.607052097371486	0.441639141291058	0.0120341857638948	25.3308244792629
2460520.5	-0.0416307147124471	0.816212953107232	-0.0171163833981609	25.7190267379977
2460522.5	0.963592780173051	0.51249904497147	-0.0959566624976275	25.7692775850715

Figure 4: Transformation coefficients of SN 2024neh over the course of 12 days. These values were calculated from transformation equations and used for adjusting between instrumental and standard magnitudes.

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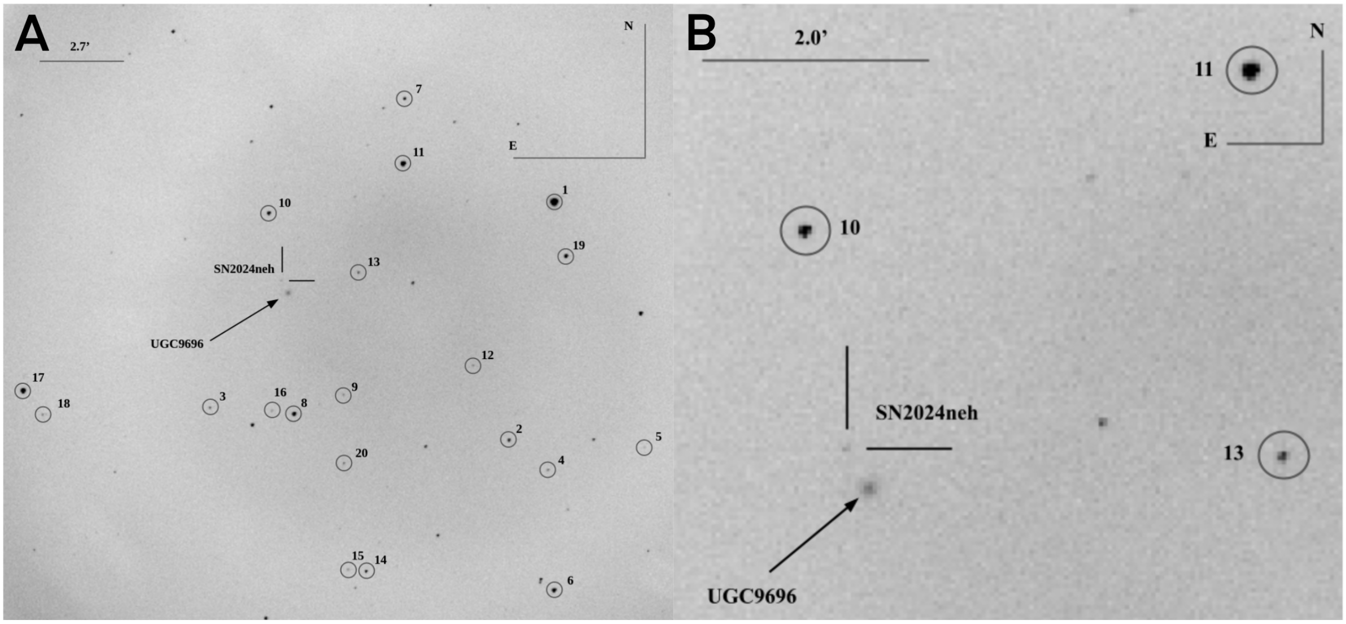

Figure 4: SN 2024neh and 20 standard stars. (A) A Charge-Coupled Device (CCD) image taken on 7/26/24 at the Leitner Family Observatory and Planetarium with SN 2024neh indicated by the black horizontal and vertical lines, its host galaxy UGC 9696 indicated by an arrow, and the 20 standard stars used for photometric calibration circled and labeled. The scale bar in the upper left represents 2.7 arcminutes. (B) Image A zoomed-in to highlight SN 2024neh. The scale bar in the upper left represents 2.0 arcminutes.

Sloan r filters were calculated and utilized to create light curves using the transformation coefficients (**Table 4**). Then, the standard deviation or uncertainty in the g band magnitude and color index was calculated using a least squares linear regression.

Light Curve Model Fitting

Models for Type Ia, Ib, IIb, IIP, and IIL supernovae were fit to the SN 2024neh light curve using a two-parameter chi-squared minimization (2). The chi-squared equation is given by:

$$\chi^2 = \sum_i^N \frac{(y-f(x))^2}{\sigma^2} \quad \text{(Equation 5)}$$

In this equation, y−f(x) is the difference between the observed values and values predicted by the model, x is the Julian Day offset, σ is the uncertainty value, and the function f represents the supernova model. Starting at value i, the chi-squared value is then calculated using N individual measurements.

This process of chi-squared model fitting was used to estimate the distance modulus of SN 2024neh as the distance modulus shift that best fits the supernova model to the observed data. The distance modulus μ0 is defined as the difference between the apparent and absolute magnitude of an object (23). To estimate the error in this distance modulus, chi-squared values are computed over a grid of trial x and y values. The pair of x and y values that return the minimum chi-squared value represent the parameters that best fit the model to the data. A heat map was utilized with the 1σ contour line plotted (Figure 3). The 1σ error for the estimated distance modulus was determined after identifying the upper and lower bounds of the central section of the 1σ contour line.

Then, we estimated the distance of SN 2024neh from the Earth by using the following equation:

$$\mu_0 = 5\log(d) + 5 \quad \text{(Equation 6)}$$

where μ0 is the estimated distance modulus and d is the distance between SN 2024neh and the Earth in parsecs. Next, to calculate the uncertainty in the distance d, we found how the uncertainty in the distance modulus μ0 affects d. We used the following equation:

$$\sigma_d = \frac{\partial_d}{\partial_{\mu_0}} \sigma_{\mu_0} \quad \text{(Equation 7)}$$

In this equation, σd represents the uncertainty in the distance to SN 2024neh and σμ0 represents the uncertainty in the distance modulus. The partial derivative σd/σμ0 indicates how sensitive the distance d is to changes in μ0.
σd/σμ0 was solved for by isolating d and then taking the partial derivative with respect to μ0. The final equation for σd was obtained by substituting this value of σd/σμ0

$$\sigma_d = \frac{\ln(10)\cdot 10^{\frac{\mu_0+5}{5}}}{5} \sigma_{\mu_0} \quad \text{(Equation 8)}$$

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