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Article

Color photometry and light curve modeling of apparent transient 2023jri

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SUMMARY

Close observation of transients, or astrophysical phenomena whose brightness varies over short periods of time, may lead to a greater understanding of our universe's dynamic evolution. Although some only last for weeks or even seconds, these short-lived transients nonetheless provide astronomers with crucial insights. Extragalactic transients, including supernovae, may contain information on star formation and evolution. Encouraged by these prospects, our team selected transient 2023jri from the Transient Name Server catalog for further analysis. We hypothesized that transient 2023jri was a supernova, a colossal explosion caused by the collapse of a dying star. Over the course of four weeks, we collected data on 2023jri using both local and remote telescopes. Using aperture photometry, we determined the standard Sloan-g and Sloan-r magnitudes of the transient on seven nights. We graphed these changing magnitudes over time to obtain 2023jri's light curve. We confirmed our hypothesis with standard light curves, ultimately classifying 2023jri as a Type IIb supernova. Finally, because Type IIb supernovae are a less researched supernova type, we further supported our research with an analysis of the color curve and spectroscopy of 2023jri.

INTRODUCTION

Astrophysical transients are extremely bright, short-lived phenomena often caused by the destruction of an astrophysical object (1). Transient duration can vary from seconds to years, as their brightness changes (1). Although some transients occur in the Milky Way, most are extragalactic, deep-space events, such as gamma-ray bursts or supernovae (1).

A supernova is a massive explosion of a star (1). Supernovae are categorized into two observational classes: Type I and Type II (1). Both classes of supernovae not only result in the creation of heavy elements but also help astronomers make groundbreaking discoveries. Type Ia supernovae, for example, are often used as standard candles, or objects with known intrinsic brightness, to measure distances in the Universe (1). These supernovae played critical roles in discoveries regarding dark energy and the accelerating universe (2). While Type I supernovae form from runaway nuclear reactions, Type II supernovae form when the star runs out of nuclear fuel and collapses under its own gravity (1). Type II supernovae occur in star-forming regions of spiral and irregular galaxies; they have not been observed in elliptical galaxies (3). Type II supernovae can be further classified as Type II-L, Type II-P, and Type IIb by analyzing their light curves and spectra. Through the analysis of both Type I and Type II supernovae, astronomers can categorize stellar events and better understand the inner workings of stars (1).

In particular, the light curve of a Type IIb supernova is characterized by two peaks, followed by a gradual decline in magnitude (4). The first peak is caused by the heating of the envelope; the second by the radioactive decay of nickel (4). Type IIb supernovae are associated with the deaths of massive stars, which lose their hydrogen-rich envelope and explode (4). Such stars must have a mass between eight to 15 solar masses (5). These Type IIb supernovae make up about 10% to 12% of all core-collapse supernovae (6), which in turn are about 76% of all supernovae (7).

Limited research has been done on Type IIb supernovae, for several reasons. Principally, Type IIb supernovae are rarely observed. The most commonly observed supernovae are Type II-P (8), and as of 2011, only 69 Type IIb supernovae have been detected (4). Fortunately, with the growing use of automated sky surveys, the number of Type IIb detections is increasing (4). Additionally, observed Type IIb supernovae may be misclassified, contributing to limited observations. Type IIb supernovae initially have strong spectral hydrogen lines, a characteristic of all Type II supernovae (4). However, these lines fade over time, and the supernova comes to resemble a hydrogen-poor Type Ib supernova (9). Thus, Type IIb supernovae are often differentiated by Type Ib supernovae by prominent spectral hydrogen lines found shortly after the explosion (4). Late observation of a fading Type IIb supernova makes this differentiation challenging and might lead to incorrectly classifying a Type IIb as a Type Ib supernova. By studying and classifying more supernovae, we actively work towards clarifying the ambiguities surrounding Type IIb supernovae.

In July 2023, our team selected the previously unclassified apparent transient (AT) 2023jri (also known as ATLAS23lqb or ZTF23aamfmqm), from the Asteroid Terrestrial-impact Alert System (ATLAS) project's Transient Name Server (10) to study and classify. Transient 2023jri was first observed by

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ATLAS on May 29, 2023, at 19:03:37 hours (60093.58 MJD), with a discovery magnitude of 16.48±0.03. 2023jri is found in the southern part of the host spiral galaxy, UGC 12639, at a right ascension of 23:30:27 and a declination of +30:13:11.35. UGC 12639 is located at a distance of 17.5±0.015 Mpc from Earth. We used a reference image of this host galaxy to confirm 2023jri's existence (11). Based on 2023jri's recent formation and its bright magnitude, our team hypothesized that the apparent transient 2023jri was a supernova.

To test our hypothesis, we spent four weeks observing 2023jri using telescopes at the Leitner Family Observatory and Planetarium at Yale University and the iTelescope network. By imaging 2023jri with two different color filters, we were able to use photometry—a process that measures the brightness or flux of stars and other objects—to determine the instrumental and standard magnitude of 2023jri each night. 2023jri's magnitude dimmed over time, giving us a light curve (a graph of its brightness over time) that we fit to standard light curves. We ultimately classified AT2023jri as a rare Type IIb supernova with a peak magnitude around May 19, 2023. We also determined 2023jri's color curve (the change in 2023jri's color over time) and analyzed its spectrum to confirm our classification.

RESULTS

Imaging

AT2023jri (**Figure 1B**) is located in the host galaxy UGC 12639 at a right ascension of 23h 30m 27s and a declination of +30° 13' 11.35" (J2000 coordinates). After observing these coordinates through Charge-Coupled Device (CCD) and Complementary Metal Oxide Semiconductor (CMOS) images, we found that supernova AT2023jri is clearly distinguishable from its host galaxy (**Figure 1**). We took images of 2023jri with varying speed, clarity, and magnification by using different focal length to aperture ratios (f/#) on telescopes where smaller f/# indicates lower magnification but wider field and greater brightness (12). For this, we used the following telescopes: 0.50-meter f/6.8, 0.61-meter f/6.5, or 0.32-meter f/8.0 telescopes from the iTelescope network or the 12-inch Meade SCT f/10 or 16-inch Ritchey-Chretien Telescope f/8.9 at Yale University.

We utilized two sets of color filters, Johnson V ("visual") and R ("red"), which have central wavelengths of 366 and 435 nm respectively, and Sloan g and r filters, which have central wavelengths of 477 and 623 nm respectively. In this paper, "v" and "r" refer to raw instrumental magnitudes; "V" and "R" refer to standard V and R magnitudes, which are calibrated magnitudes that were corrected for unintended atmospheric and instrumental effects.

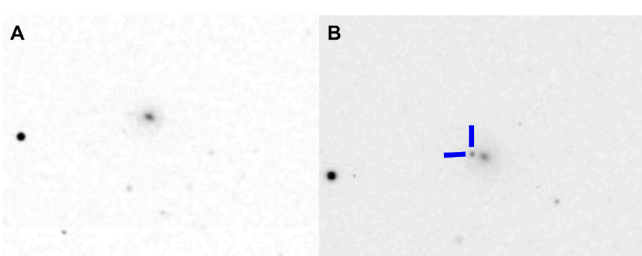

Figure 1: Confirmation of 2023jri's existence. (A) A Charge-Coupled Device (CCD) reference image of UGC 12639 used to confirm AT2023jri's existence (NED, 2023). (B) a CCD image of UGC 12639, taken on 7/05/23, with SNe 2023jri identified by the blue lines. It is clearly distinguishable from its host galaxy.

JDN	Std V Mag	Std R Mag	Color (v-r)
2460131.569	17.18 ± 0.07	17.72 ± 0.07	-0.54
2460141.531	17.51 ± 0.13	18.06 ± 0.13	-0.55
2460145.563	17.34 ± 0.10	18.01 ± 0.10	-0.68
2460147.479	17.69 ± 0.10	18.47 ± 0.10	-0.78
2460155.625	17.69 ± 0.03	18.36 ± 0.03	-0.68
2460156.485	17.88 ± 0.06	18.45 ± 0.06	-0.57
2460159.479	18.32 ± 0.21	18.98 ± 0.21	-0.66

Table 2: Calibrated V Magnitudes vs Time fitted with Type IIb light curve model. The standard V magnitudes of 2023jri over time, fitted with a standard Type IIb light curve. The orange curve is the fitted model and the points with error bars represent the calculated magnitude and standard deviation.

Calibrating Magnitudes and Fitting Light Curves

In order to test the hypothesis that transient 2023jri is a supernova, our team determined the calibrated magnitudes of 2023jri in two colors. Using aperture photometry and color calibration, we calculated the standard V and R magnitudes of 2023jri on seven nights (**Table 1**). Our results showed a decreasing trend in magnitude over time, supporting our hypothesis that transient 2023jri was a supernova (**Figure 2, 3**).

After obtaining the calibrated magnitudes of 2023jri on 7 separate nights between July 6, 2024, and August 2, 2024, our team created plots of 2023jri's light curve. On the x-axis, we plotted the number of days since the peak magnitude. On the y-axis, we plotted 2023jri's standard V or R magnitude. We then fit standard supernova light curve models to the light curve of 2023jri. In order to determine which model best fit 2023jri's light curve, we compared the root mean squared errors (RMSE) of each model. Out of the five models for Types Ia, Ib, IIb, II-L, and II-P, Type IIb gave the lowest RMSE for both the standard V magnitude light curve (2.15±1.47) and standard R magnitude light curve (2.03±1.42) (**Table 2**).

After determining that the Type IIb model was the best fit for 2023jri's light curve, we predicted that the first peak magnitude of 2023jri occurred at about 2460083.785 JD, or 6:50:24.00 UT on May 19, 2023. This is about 40 days before our first observation (**Figure 2, 3**).

Color Index Curve

We also produced a color index curve of 2023jri, where apparent V-R is plotted against days since the peak magnitude. We fitted a least squares regression line (LSRL) to determine the general trend in color over time (**Figure 4**). The negative slope of the LSRL indicates the gradual cooling and reddening of 2023jri over time.

DISCUSSION

Through close analysis of transients such as supernovae, we can better understand our ever-evolving universe.

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Motivated by a desire to supplement current knowledge of supernovae, our team observed apparent transients in search of a supernova. We hypothesized that the apparent transient 2023jri was a recently formed supernova. Over the course of four weeks, consistent data collection of the magnitude and color of 2023jri confirmed our hypothesis that we had found a rare supernova type, established that its peak magnitude occurred roughly 40 days prior to our first time point, and demonstrated that it is progressively cooling.

We concluded that 2023jri is a Type IIb supernova. The root mean square values for the Type IIb fit were the smallest for both our V and R magnitudes, and the graph of the fitted light curve showed similarity to the Type IIb model (**Figure 2, 3**), supporting our hypothesis that 2023jri is not just a supernova, but a rare Type IIb supernova.

Type IIb supernovae in their late stages are very similar to Type Ib supernovae. This similarity is reflected in our RMSEs, where the root mean square values for Type Ib fits to our V and R data are the third-to-least and second-to-least RMSE, respectively. Our results would improve with continued observation; however, due to a lack of time and equipment, our team could neither continue observing nor determine 2023jri's spectrum.

To supplement our work, we researched other factors that could confirm 2023jri's classification as a Type IIb supernova. First, UGC 12639 is a spiral galaxy, and Type II supernovae only form in spiral and irregular galaxies. However, the same can be said about Type Ib supernovae (13). To differentiate these possibilities, we sought to identify the presence of hydrogen lines and the lack of helium lines in the spectrum of a Type IIb supernova just after the progenitor star explodes. After two weeks, the hydrogen lines of a Type IIb supernova fade quickly, and helium lines appear (14). Unfortunately, our calculations show that our first observation on July 5 was about 40 days after 2023jri's peak magnitude. Furthermore, due to the unavailable 12-inch telescope, we did not have access to equipment to do spectroscopy. However, the ATLAS group published a spectrum of 2023jri after its discovery. Their spectrum depicts prominent hydrogen emission lines and minimal helium emission lines (10). Because Type Ib supernovae rarely have hydrogen lines in their spectra, this is a good indicator that 2023jri is a Type IIb supernova.

Additionally, the RMSE values between our data and the Type II-L model curve were relatively similar to that of the Type IIb model. We conducted further research on Type II-L supernovae to identify discrepancies with Type IIb supernovae. Type II-L supernovae are typically identified by their distinctive light curve shape (15). The light curves of Type II-L supernovae (the "L" stands for "linear") have long periods of linear decay that may last for hundreds of days (9). The more rapid decrease in 2023jri's magnitude in just 30 days of observation validated our decision to reject a Type II-L classification.

An analysis of our color versus time graph also presents evidence of a Type II supernova. (16) shows that the slope of a Type II supernova's color curve is initially very steep, before plateauing after 40 days. This is consistent with the small slope of our color versus time graph, whose data was obtained about 40 days after peak magnitude. Although we did not obtain data during the first 40 days after the star went supernova, this plateau in color index is characteristic of a Type II supernova. More observations over a longer period of time may have reduced uncertainty and provided a stronger, more distinct trend in color value.

We conclude that 2023jri is a Type IIb supernova. Its similarities to Type Ib supernovae make 2023jri an interesting object. Compared to more common supernova types, such as Type Ia, the research on Type IIb supernovae is limited. Further research into the distinct characteristics of Type IIb supernovae would help astronomers correctly classify Type IIb and Ib supernovae. Correct classification of these supernovae also opens the opportunity to research the unique evolution and features of these supernovae. To this end, we have made our standard V and R magnitudes available via the AAVSO database to aid others in future research.

MATERIALS AND METHODS

Observing and Gathering Data

We relied on two data-gathering methods to evaluate

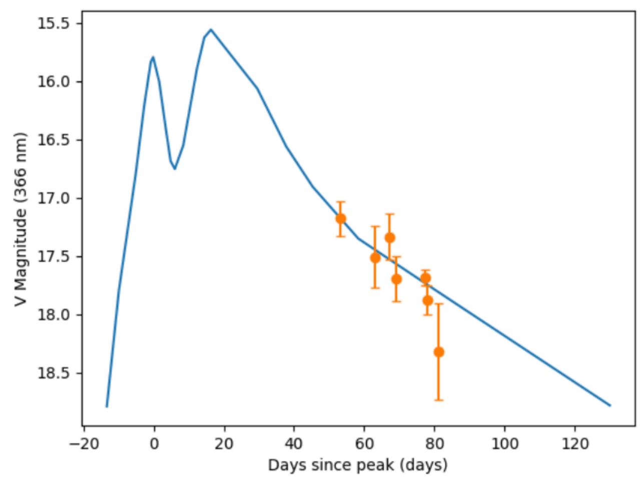

Figure 2: Calibrated V Magnitudes vs Time fitted with Type IIb light curve model. The standard V magnitudes of 2023jri over time, fitted with a standard Type IIb light curve. The orange curve is the fitted model and the points with error bars represent the calculated magnitude and standard deviation.

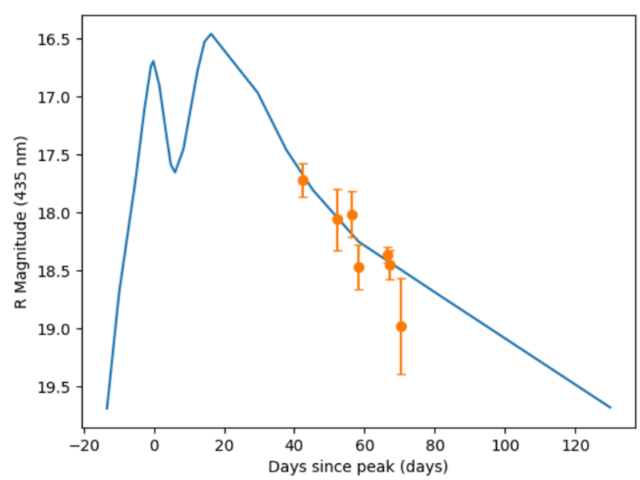

Figure 3: Calibrated R Magnitude vs Time fitted with Type IIb light curve model. The standard R magnitudes of 2023jri over time, fitted with a standard Type IIb light curve. The orange curve is the fitted model and the points with error bars represent the calculated magnitude and standard deviation.

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Model	RMSE (V)	RMSE (R)
Type Ia	6.97 ± 2.64	7.60 ± 2.76
Type Ib	2.31 ± 1.52	2.10 ± 1.45
Type IIb	2.15 ± 1.47	2.03 ± 1.42
Type II-L	2.34 ± 1.53	2.58 ± 1.61
Type II-P	2.21 ± 1.49	12.43 ± 3.53

Table 2: Root mean squared errors (RMSE) from fitting standard light curves to V and R magnitude light curves. The Type IIb model gave the lowest RMSE for both curve fits, indicating that it provided the best fit for 2023jri's light curve.

2023jri: local and remote observation. We scheduled remote telescope observation times using iTelescope, a network of telescopes around the world offering access to digital imaging services. The telescopes that we used—T18, T24, and T30—were stationed in Australia, California, and Spain, respectively. iTelecope's professional telescopes provided us with good data that could be processed easily. In total, we collected five nights of usable data from iTelescope. At Leitner Observatory in New Haven, Connecticut, we used a 12-inch and a 16-inch telescope to observe 2023jri (**Table 3**) and obtained two nights of usable data. To take local data, we set up the 12-inch Meade SCT or the 16-inch Ritchey-Chretien Telescope and slewed to a calibration star and then to our supernova. Once the supernova was confirmed to be within the camera's field of view, we took images using Sloan g and Sloan r filters, which isolate light at wavelengths of about 477 and 623 nm, respectively. Sub-exposure time for all images was 60 seconds; depending on weather and time constraints, between 10 and 20 sub-exposures were taken with each filter. At least five darks were taken each night. Between July 7 and August 2, we completed two successful nights of local observing and five nights of remote observing using iTelescope. The main issues preventing us from having successful in-person observations were weather, tracking errors, and equipment malfunctions. We overcame these issues by rejecting images with clouds and tracking errors.

Aperture Photometry and Calibration

To calibrate and combine our images, we used MaxIm DL, an image processing software. By median-combining all dark and flat frames, we created master darks and master flats. To calibrate each Sloan-g and Sloan-r photos, we subtracted the master dark frame and divided by the master flat frame (17, 18). Next, we median-combined the calibrated images to obtain master V and R images. Using AstroImageJ, another image processing software, we used aperture photometry to measure the flux of 10-20 calibration stars. To determine flux, we selected a 6-pixel-radius circular aperture around a star and used AstroImageJ to add the pixel values within the aperture and then subtracted the average background pixel value from a 4-pixel-width annulus. We transformed these values into instrumental magnitudes by using the following equations:

$$v = -2.5\ log\ (Flux_v) \quad (1)$$

$$r = -2.5\ log\ (Flux_r) \quad (2)$$

Through the American Association of Variable Star Observers' Photometric All Sky Survey (APASS) Data Release 10 (19), we obtained the standard magnitudes, right ascensions, and declinations of our calibration stars. Using this data, we plotted right ascension versus declination to create finder charts that plotted each star with its corresponding standard V and R magnitude.

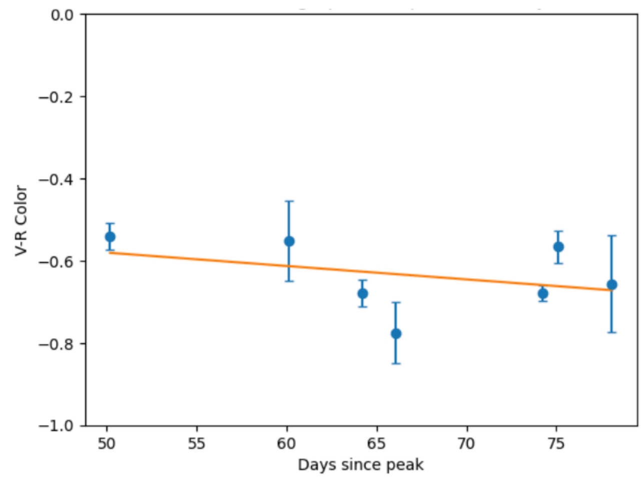

Figure 4: Color vs Time graph for supernova 2023jri. The color index of 2023jri V-R magnitudes of 2023jri over time. The downward linear regression line indicates that the supernova is cooling or reddening.

After obtaining both the standard and instrumental magnitudes of the calibration stars in V and R, we calibrated our data by using a least squares regression line (LSRL) that we coded in python. A LSRL was fit to both a (v-r) versus (V-R) graph and (V-R) versus (V-v) graph to obtain the T_{vr}, C_{vr}, T_v, and C_v transformation coefficients. These linear equations are listed below:

$$(V - R) = T_{vr}(v - r) + C_{vr} \quad (3)$$

$$(V - v) = T_v(v - r) + C_v \quad (4)$$

$T_{vr}, C_{vr}, T_v, C_v,$	Transformation Coefficients
V	Standard Green Magnitude
R	Standard Red Magnitude

Once the transformation coefficients were calculated, we used AstroImageJ to measure the flux of the supernova. Using these fluxes, we calculated 2023jri's instrumental magnitudes (Equations 1, 2). Then we were able to use Equation 3 to calculate the difference between 2023jri's standard magnitudes (V-R) and Equation 4 to calculate the standard V magnitude. This allowed us to use standard V magnitude to calculate 2023jri's standard R magnitude from (V-R). The color of the supernova was obtained by calculating the difference between the supernova's instrumental v and r magnitudes. This process was then repeated for all seven nights of observation. Previous application of these transformation equations to standardize supernova magnitudes was performed by (20).

Error for each standard magnitude calculation was calculated by fitting an LSRL to the (v-r) and (V-R) data and another LSRL to the (V-R) and (V-v) data. The standard deviation of each graph was calculated using Equation 5 (the residual is divided by N-2 because there are two degrees of

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JDN	Camera
2460131.569	T24
2460141.531	T24
2460145.563	T30
2460147.479	12 inches
2460155.625	T18
2460156.485	T18
2460159.479	16 inches

Table 3: Observation specifics over 7 nights. Parameters include date in Julian Day Number format and camera type. All dates used V/R filters and 60 seconds of total exposure.

freedom). These uncertainties were then combined to give the final uncertainty for that night. Note that these margins of error are also represented on the color index curve–any visual variation is due to the scale of the y-axis.

$$\sigma = \sqrt{\frac{\sum (x_i - \mu)^2}{N-2}} \quad (5)$$

$$\sigma_F = \sqrt{{\sigma_1}^2 + {\sigma_2}^2} \quad (6)$$

σ Standard Deviation

σ_f Standard Deviation from V-r vs v-r graph

$\sigma_{1,2}$ Standard Deviation from V-r vs V-v graph

σ_F Final Error

After obtaining standard magnitudes, we plotted the light curve (magnitude versus time) of 2023jri. Our data was compared to standard light curve models for Type Ia, Ib, IIb, II-L, and II-P supernovae. Standard light curve models were obtained from the Yale-Potsdam Stellar Isochrone (YaPSI) grid's free open-source code, which uses a Monte Carlo Markov-chain tool (21). The use of YaPSI code is demonstrated by (22). The model that best fit our data was found using a root mean square function in python (Equation 7) that interpolated the predicted values at the observation dates linearly between the two nearest x-coordinate model points (Equation 7). Note that interpolation is common and acceptable in astronomy (23). Errors for root mean square values were then calculated using Equation 8. After our data was fit to the standard light curve on a magnitude versus time graph, we used the peak of the standard light curve to estimate the date of 2023jri's peak magnitude.

$$\text{Mean Square Error} = \sum \frac{(y - f(x))^2}{\sigma^2} \quad (7)$$

$$\text{Root Mean Square Error} = \sqrt{\chi^2} \quad (8)$$

A similar method for supernova classification via modeling and (V-R) color index was conducted by (24), involving different transformation equations to determine standard magnitude from instrumental magnitudes. (24) was successful in producing 51 light curves of Type II supernovae, some of which were Type IIb supernovae.

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