KRITTIKA SUMMER PROJECTS 2024

# Study of the Nearest Hydrogen-Rich Core-Collapse Supernova: SN 2023ixf

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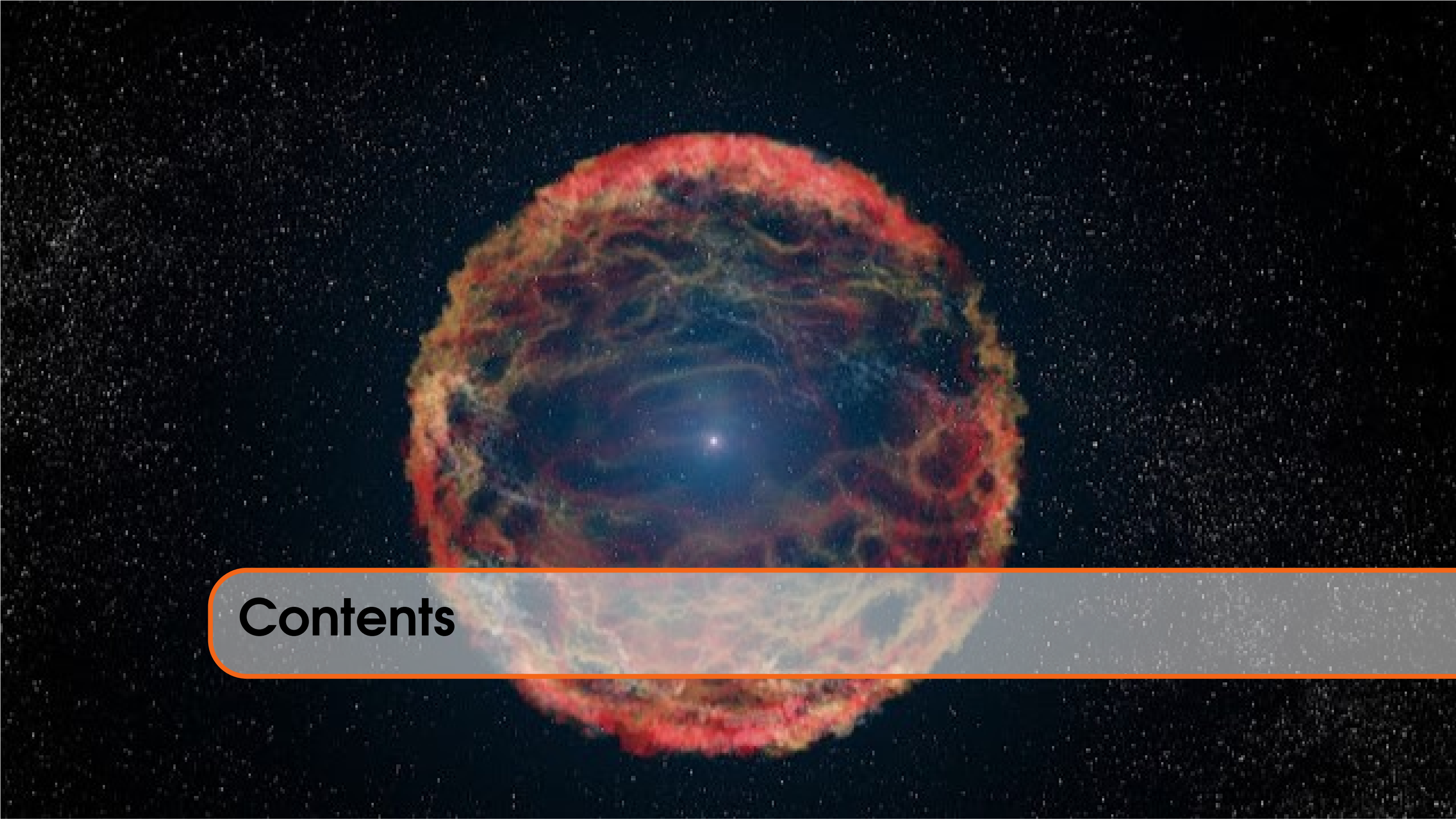
# Abstract

This study presents a comprehensive analysis of SN2023ixf, a Type II-L core-collapse supernova, using observational data from the Growth-India Telescope and publicly available sources. We employed various photometric techniques, including challenging U-band observations, to construct detailed multi-band light curves. The supernova exhibited an unusually early peak, suggesting interesting circumstellar material interactions. Through sophisticated modelling using tools such as SuperBol, we estimated key physical parameters including the $^{56}$Ni mass (0.0308 ± 0.0003 $M_{\odot}$), ejecta mass ( 6 $M_{\odot}$), and explosion energy (between $10^51$ to $10^52$ erg), assuming a progenitor radius of 350 $R_{\odot}$. Our results contribute to the understanding of Type II-L supernovae and provide insights into the progenitor star's properties and explosion dynamics. The study also highlights areas for future research, including long-term monitoring, spectroscopic analysis, and refinement of U-band photometry models.



# Contents

# 1. Introduction

## 1.1 Supernovae

A supernova is what happens when a massive star's core (> 8 $M_\odot$) implodes. Supernovae are classified into two main types: Type I and Type II, based on their spectral characteristics. Type I supernovae lack hydrogen lines in their spectra and are further subdivided into Types Ia, Ib, and Ic. Type II supernovae show strong hydrogen lines. The primary difference lies in their progenitor stars and explosion mechanisms. Type Ia results from a white dwarf in a binary system, while Types Ib, Ic, and II are core-collapse events of massive stars. Studying supernovae is crucial in astrophysics as they provide insights into stellar evolution, nucleosynthesis, and cosmic distance measurements. They serve as laboratories for extreme physics and play a vital role in galactic chemical enrichment. Supernovae significantly impact the interstellar medium by injecting energy, heavy elements, and shock waves. This process triggers star formation, shapes galactic structure, and drives the chemical evolution of galaxies.

## 1.2 SN2023ixf: A Core Collapse Supernova

A core-collapse supernova occurs when a massive star exhausts its nuclear fuel. The star's core collapses under gravity, forming a neutron star or black hole. The outer layers rebound, creating a powerful explosion. This process releases an enormous amount of energy and ejects the star's outer layers into space. Characteristic features of core-collapse supernovae include a rapid increase in brightness followed by a gradual decline, the presence of elements like hydrogen, helium, and heavier elements in their spectra, and the potential formation of a compact remnant. They often show evidence of interaction with the surrounding circumstellar material, which can provide clues about the progenitor star's evolution and mass loss history.

## 1.3 Objectives

The primary objectives of this study on SN2023ixf are multifaceted. First, it aims to analyse observational data from the Growth-India Telescope to construct detailed light curves across different filters, tracing the supernova's brightness evolution over time. This will provide crucial information about the explosion energy, ejecta mass, and the properties of the progenitor star. Second, the study seeks to integrate publicly available data from various sources to build a comprehensive understanding of SN2023ixf, potentially revealing unique characteristics or similarities with other known supernovae. Finally, through sophisticated light curve modeling and comparison with historical supernovae, the project aimed to constrain the physical properties of the supernova emission and its surrounding environment.

# 2. Methods

## 2.1 Image reduction

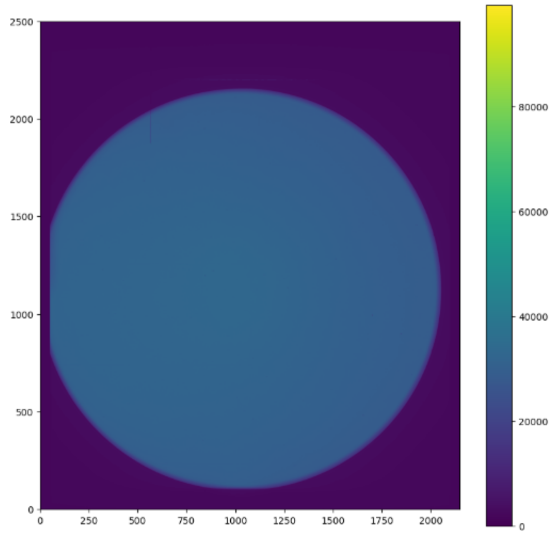
Image reduction in astronomical data analysis serves to correct for various artifacts and instrumental effects that can affect the quality and accuracy of observational data. The primary purpose is to remove systematic errors and noise from raw images, allowing astronomers to extract meaningful scientific information. In the context of the SN2023ixf study, image reduction was a crucial step in preparing the data obtained from the Growth India Telescope (GIT) for analysis. This process ensures that the measurements of the supernova's brightness are as accurate as possible, which is essential for constructing reliable light curves and performing subsequent analyses.

The basic formula which was followed is :

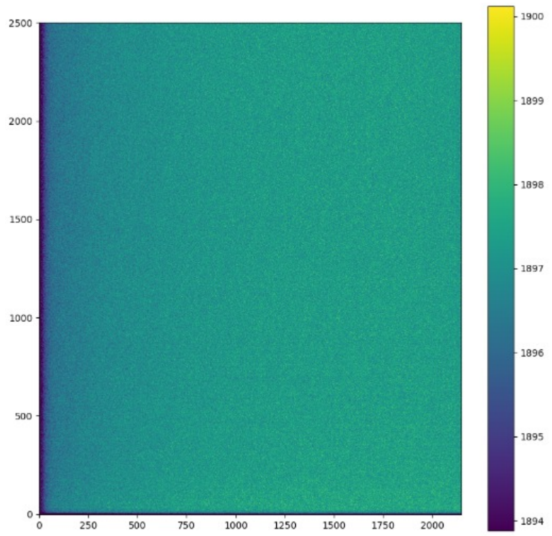
$$\text{Reduced Image} = \frac{\text{Image} - \text{Bias frame}}{\text{Flat frame}} \tag{2.1}$$

### 2.1.1 Bias frames and flat frames

Bias frames and flat frames are two key components in the image reduction process. Bias frames are used to correct for the inherent electronic noise in the detector, which is present even when no light is hitting the sensor. They are typically short exposures taken with the camera shutter closed. Flat frames, on the other hand, are used to correct for variations in pixel sensitivity across the detector and for any optical imperfections in the telescope system. Flat frames are usually taken by pointing the telescope at a uniformly illuminated surface or the twilight sky. The difference between bias and flat frames lies in their purpose: bias frames correct for electronic offsets, while flat frames address optical and detector non-uniformities. Both are essential for producing clean, calibrated images that accurately represent the astronomical scene being observed.




(a) Flat frame




(b) Bias frame

Figure 2.1: Example frames

### 2.1.2 Astrometry

Astrometry is the science of precisely measuring the positions, motions, and distances of celestial objects. In the context of this project, astrometry was performed using nova.astrometry.net, an online tool that automates the process of plate solving - matching observed stars in an image to known star catalogs. Astrometry involves several aspects: star detection, pattern matching, calibration, and positional accuracy. The process converts the x and y pixel coordinate system of the image into a world coordinate system (WCS) namely RA-Dec. This step is crucial for accurately identifying the position of SN2023ixf in the sky and for aligning multiple observations taken at different times. The output of this process is a WCS.fits file, which contains the necessary information to map image pixels to precise celestial coordinates.

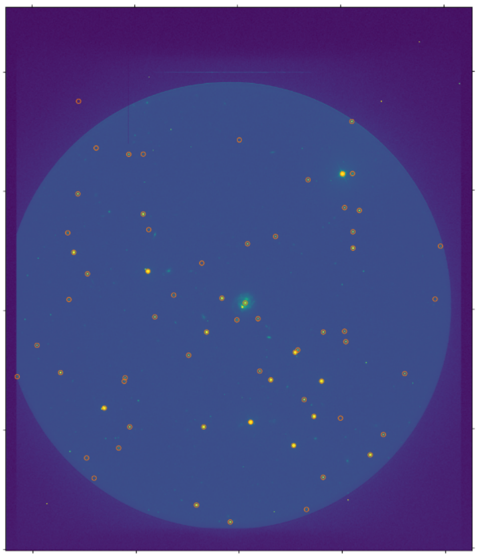


Figure 2.2: Image with recognised sources-encircled

## 2.2 Photometry

Photometry is the measurement of the brightness of celestial objects. In this study, it's used to calculate the brightness of SN2023ixf over time, allowing researchers to plot light curves and uncover details about stellar evolution. The project employed two main types of photometry: aperture photometry and Point Spread Function (PSF) photometry. Aperture photometry measures the total flux within a defined circular area around the object, while PSF photometry models the brightness distribution of point sources.

## 2.3 Why PSF?

PSF photometry offers several advantages over aperture photometry, particularly in crowded fields or for faint objects. It can more accurately separate the light of overlapping sources and is less affected by background noise. PSF photometry also allows for more precise measurements of object positions. In this study, both methods were explored. Aperture photometry tool was used for aperture photometry.

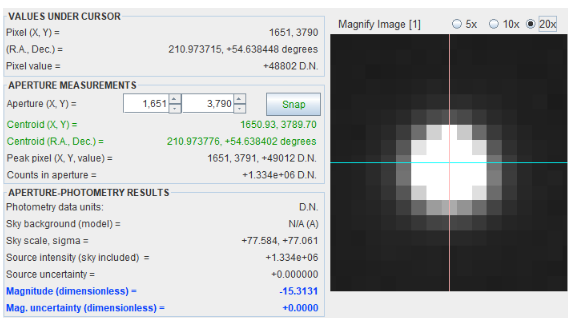
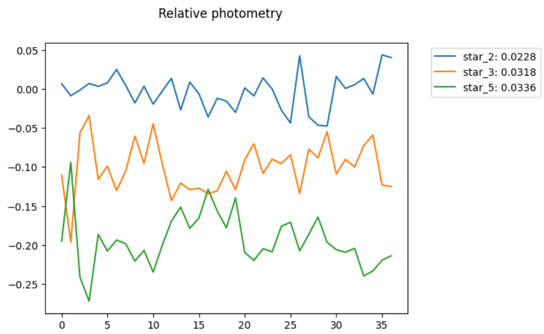
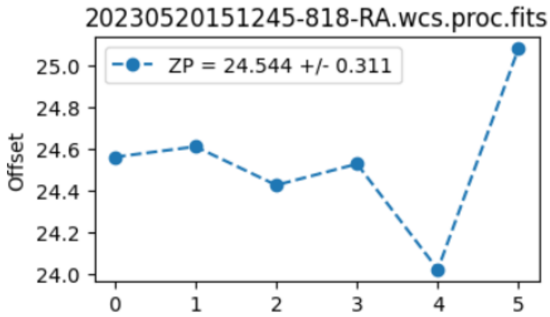



Figure 2.3: Using APT

PSF photometry was particularly emphasized for its potential to handle challenging observational conditions. SExtractor (Source Extractor) contributes to PSF photom-




(a) Relative Photometry




(b) Offset plot

Figure 2.4: Example plots

etry by detecting and cataloging sources in the astronomical images. It provides initial estimates of source positions, fluxes, and shapes, which are then used as inputs for PSF fitting. PSF fitting involves modeling the brightness distribution of point sources in the image. This model is then used to measure the brightness of individual objects more accurately, especially in crowded fields.

### 2.3.1 U-band photometry

U-band photometry refers to measurements taken in the ultraviolet part of the electromagnetic spectrum. It's particularly challenging due to atmospheric absorption but provides valuable information about the hottest and most energetic phenomena in supernovae. In this study, U-band photometry was used to complement observations in other wavelengths, offering insights into the early, high-temperature phases of SN2023ixf's evolution. The process involved careful calibration and error analysis to overcome the challenges associated with U-band observations.

#### Relative photometry

Relative photometry is a technique where the deviation in magnitude of the target object (various stars) from the average/background magnitude. This method helps to checks for variations across days, if an object's deviation across days varies more than other objects, it is said to be relatively more variable. In U-band photometry, relative photometry was applied to select appropriate stars for calibration.

#### Offset plots

Offset plots were also used in U-band photometry. These plots show the difference between the measured magnitude of reference stars and their known (catalogue) magnitudes for a specific file. In the project, offset plots were used to identify outlying stars, which were removed from the calibration. The median and standard deviation of these offsets were then used to calculate zero points and errors for each image, allowing for more accurate U-band magnitude calculations for SN2023ixf.

## 2.4 Modelling

Modelling in this project serves multiple purposes, primarily to derive physical parameters of the supernova that can't be directly observed. Tools and approaches:

The study also explored the plausible range of ejecta masses and explosion energies for given progenitor star radii, using equations from published literature ((2)).

### 2.4.1 SuperBol

The SuperBol package is a Python-based tool designed for supernova analysis. In modelling, it was used to convert the observed magnitudes(taken from publicly available data) in different bands into bolometric (total) luminosity. This process involved fitting a blackbody curve to the spectral energy distribution at each epoch, which allowed to estimate the supernova's temperature and radius evolution over time.

### 2.4.2 Estimation of $^{56}$Ni

Nickel-56 ($^{56}$Ni) is a radioactive isotope produced during the supernova explosion. By fitting models to the observed light curve, the amount of $^{56}$Ni produced was estimated, which in turn provided information about the explosion energy and the mass of the progenitor star. The slope of the late-time light curve is particularly important for this estimation, as it directly relates to the rate of Ni56 decay, as the decay of Ni56 powers the later stages of the supernova light curve.

# 3. Results

## 3.1 Light curve

This(Figure 3.1) multi-band light curve provides valuable insights into the evolution of supernova SNIXF2023. The data captures the supernova's behaviour across four photometric bands (u, g, r, and i). The light curve exhibits a clear rise to peak brightness followed by a linear decline, characteristic of a Type II-L supernova. The u-band, while more sparsely sampled, shows a steeper decline, as expected due to increased line blanketing in the ultraviolet region as the ejecta cool. There is an unusually early peak in its light curve, which is noteworthy for core-collapse supernovae. This early peak provides insights into how supernovae interact with their circumstellar medium (CSM). The supernova's brightness evolution across different wavelengths, including the U-band, offers clues about its temperature evolution and the composition of its ejecta.

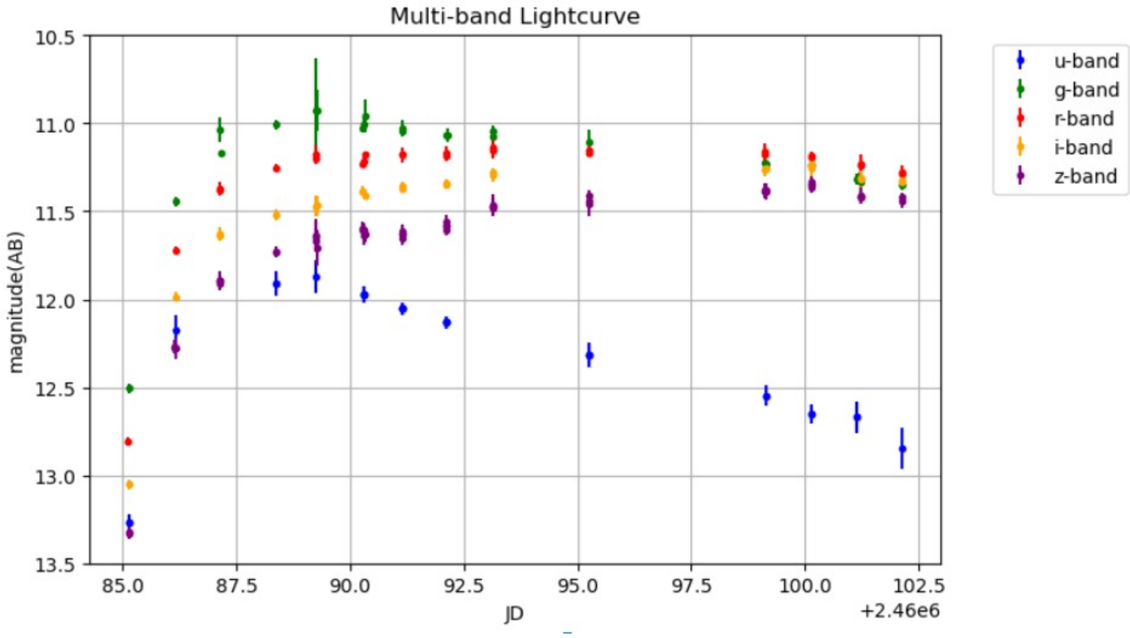



Figure 3.1: Obtained light curve

## 3.2 Modelling

The bolometric light curve of the supernova, along with the evolution of the blackbody temperature and radius over time, were constructed using the publicly available photometric data and the Superbol code, as presented in figure Figure 3.2

## 3.3 Estimation of $^{56}$Ni

The mass of Ni56 in the explosion was estimated by curve fitting the plot of observed luminosity over days (Figure 3.3). It was found out to be 0.0308 +- 0.0003 $M_{\odot}$

## 3.4 Estimation of Ejecta mass and Explosion energy

With the estimated $^{56}$Ni mass, a formula ((1)) was employed to calculate the ejecta mass and energy at a given radius. A plot(Figure 3.4) of ejecta mass and energy versus radius was created, providing a rough estimate of these parameters. Assuming the radius of supernova to be 350 $R_0$, we approximated the values for Ejecta mass is around $6M_{\odot}$ and Explosion energy is between $10^{51}$ to $10^{52}$.

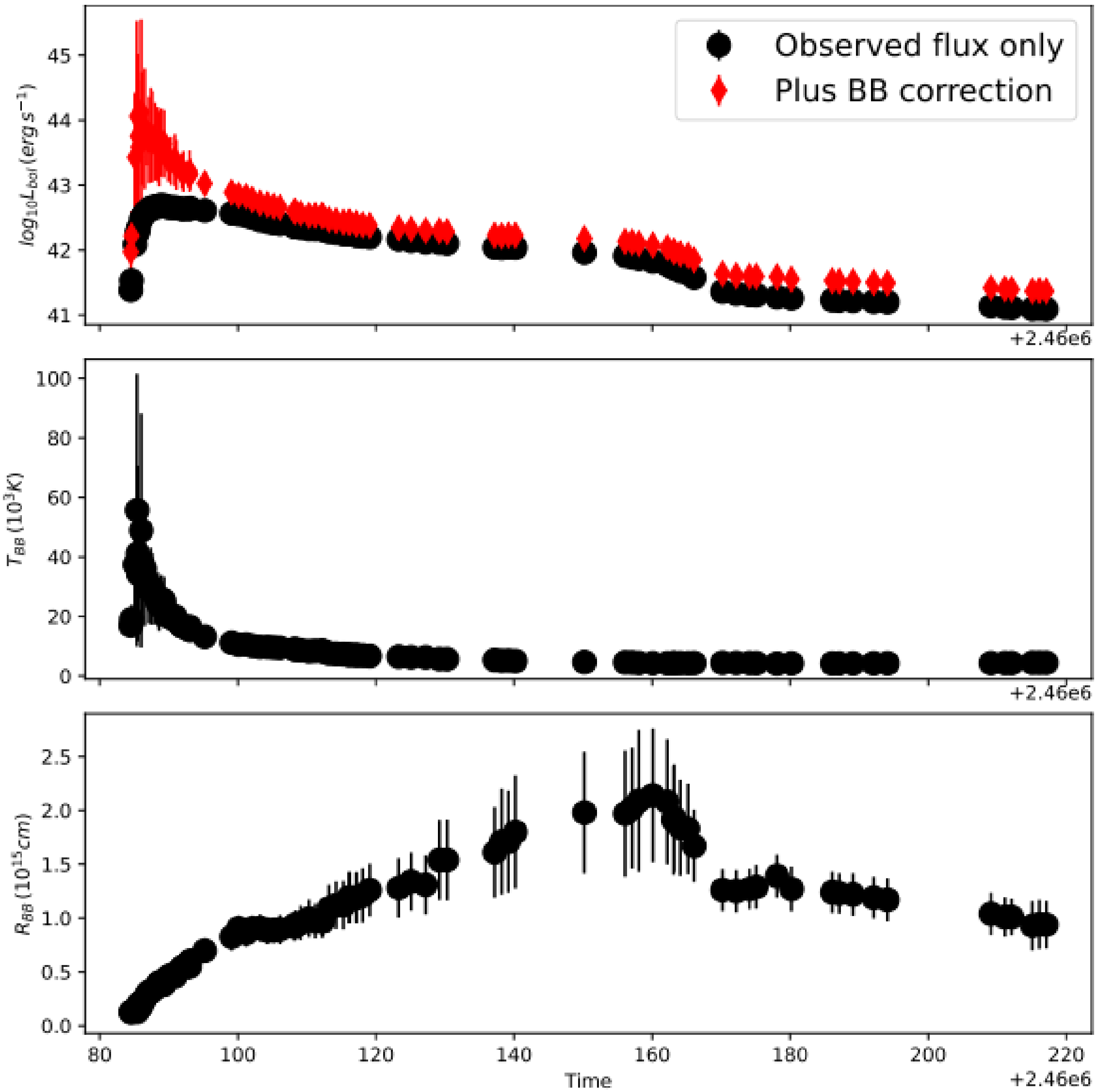



Figure 3.2: Plots obtained by Superbol

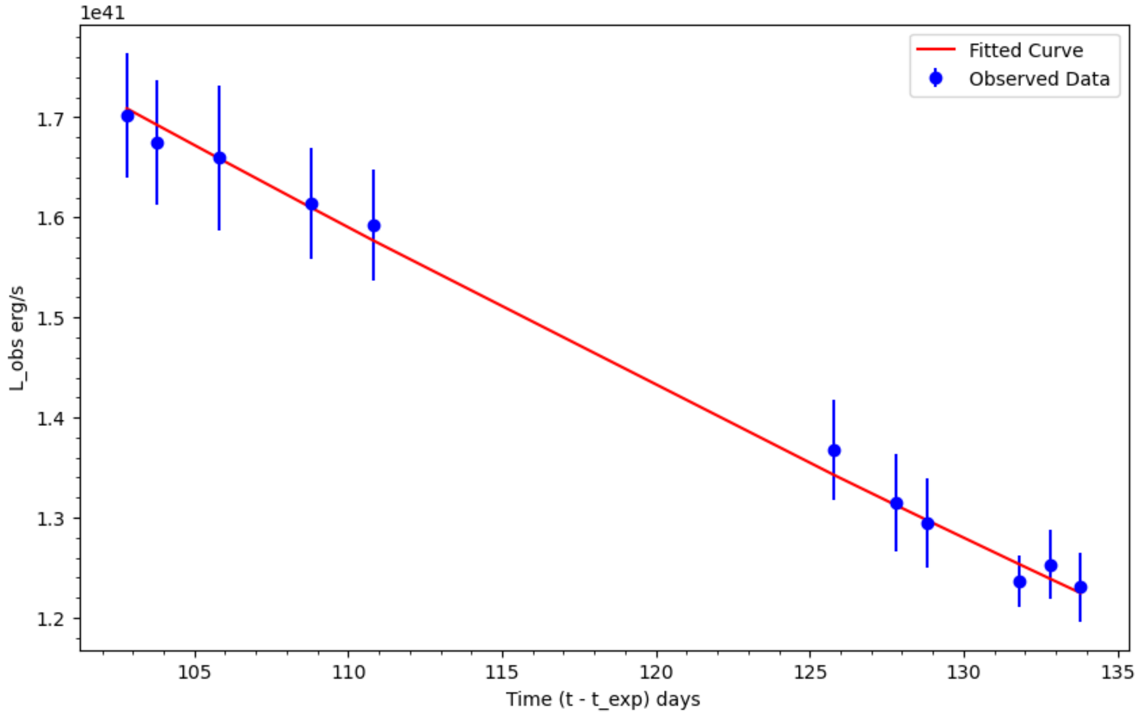



Figure 3.3: Plot for estimating $^{56}Ni$

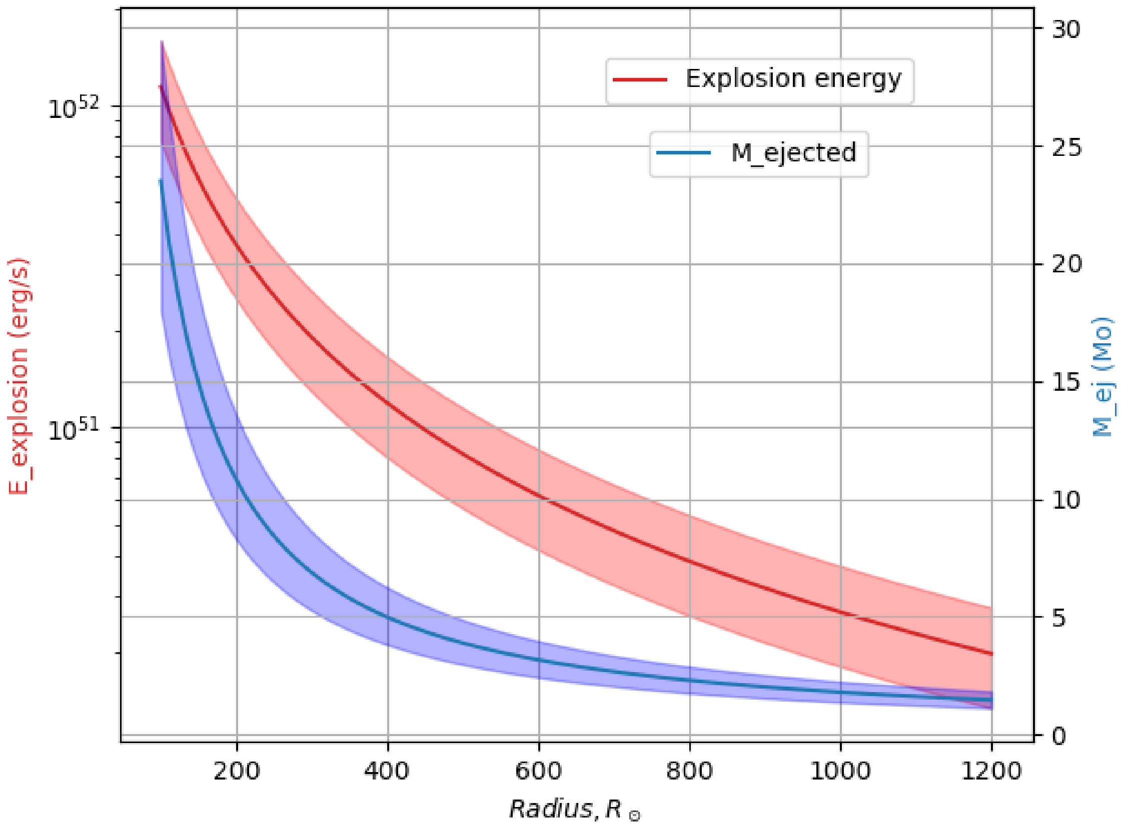



Figure 3.4: Plot for estimating Ejecta mass and Explosion energy

# 4. Conclusion

## 4.1 Comparison of Results with SN 2021wvw

The estimates of $^{56}$Ni mass, ejecta mass, and energy are in reasonable agreement with expectations just like the bolometric light curve constructed using publicly available data(2). However, a discrepancy arises from the constructed light curve. Specifically, the U-band peak is lower than expected, despite careful consideration of the photometric challenges in this band, suggesting for better reference stars for calibration.

## 4.2 Summary

The main findings of this project contribute to understanding of SN2023ixf:
1. It provides a detailed multi-wavelength light curve, including challenging U-band observations.
2. The study confirms SN2023ixf as a Type II-L supernova with an unusually early peak, suggesting interesting CSM interactions.
3. Through modelling, it offers estimates of key physical parameters like bolometric luminosity and Ni56 mass.
4. The project provides insights into the progenitor star's properties and the explosion dynamics.

## 4.3 Future studies

Future studies could focus on: 1.Long-term monitoring of SN2023ixf to track its late-time evolution and any potential interactions with more distant CSM. 2.Detailed spectroscopic analysis to complement the photometric data, providing insights into the chemical composition and velocity structure of the ejecta. 3.Comparison with other well-studied Type IIL supernovae to contextualize SN2023ixf within the broader population. 4.Refinement of models, particularly for U-band photometry, to improve agreement with observations. 5.Investigation of the progenitor star's mass loss history to explain the early light curve peak and CSM interactions. 6.Searches for any pre-explosion data that might directly reveal properties of the progenitor star.

# Bibliography


## Articles

(Tej+23) Rishabh Singh Teja et al. "Far-ultraviolet to Near-infrared Observations of SN 2023ixf: A High-energy Explosion Engulfed in Complex Circumstellar Material". In: *The Astrophysical Journal Letters* 954.1 (Aug. 2023), page L12. ISSN: 2041-8213. DOI: 10.3847/2041-8213/acef20. URL: http://dx.doi.org/10.3847/2041-8213/acef20 (cited on page 14).

## Software

Atrometry: nova.astrometry.net
Superbol: https://github.com/JALusk/Lumiere
APT: www.aperturephotometry.org
ds9: https://sites.google.com/cfa.harvard.edu/saoimageds9

## Miscellaneous

(Tej+24) Rishabh Singh Teja et al. *SN 2021wvw: A core-collapse supernova at the sub-luminous, slower, and shorter end of Type IIPs*. 2024. arXiv: 2407.13207 [astro-ph.HE]. URL: https://arxiv.org/abs/2407.13207 (cited on pages 11, 17).