Study of Nearest Hydrogen-rich Core Collapse Supernova - SN2023ixf

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1 Introduction to Supernova

A supernova is a powerful and luminous explosion that occurs during the final stages of a massive star's life cycle. This cataclysmic event results in the sudden release of an immense amount of energy, causing the star to outshine an entire galaxy for a short period. Supernovae play a crucial role in the cosmos by dispersing elements heavier than iron into space, contributing to the formation of new stars, planets, and even life.

Supernovae are classified into two main types based on their underlying mechanisms and the nature of the progenitor star:

1.1 Type I Supernova

Type I supernovae occur in binary star systems, where one of the stars is a white dwarf. A white dwarf is a dense remnant of a star that has exhausted its nuclear fuel. These supernovae are further divided into several subtypes, the most notable being Type Ia.

Type Ia Supernova: This subtype is triggered when a white dwarf accretes matter from its companion star, eventually reaching the Chandrasekhar limit (about 1.4 times the mass of the Sun). At this point, the white dwarf undergoes a runaway thermonuclear explosion, completely disintegrating the star. Type Ia supernovae are particularly important in astronomy because they have a consistent peak brightness, making them valuable as standard candles for measuring cosmic distances.

1.2 Type II Supernova

Type II supernovae occur when a massive star, typically more than eight times the mass of the Sun, exhausts its nuclear fuel. Without the outward pressure generated by nuclear fusion, the core of the star collapses under gravity, leading to a catastrophic explosion. These supernovae are characterized by the presence of hydrogen lines in their spectra.

Core-Collapse Supernova: The most common Type II supernova is the core-collapse supernova. As the core collapses, the outer layers of the star are ejected into space at high velocities, creating a shock wave that produces the supernova's bright emission. The core may eventually become a neutron star or a black hole, depending on the mass of the progenitor star. Core-collapse supernovae play a vital role in enriching the interstellar medium with heavy elements and driving the evolution of galaxies.

2 Detailed Study of Supernova SN2023ixf

Supernova SN2023ixf, discovered on May 19, 2023, has drawn significant attention from the astronomical community due to its unique characteristics and proximity to Earth. At a distance of only 6.8 megaparsecs (Mpc), or approximately 22 million light-years, it is one of the closest supernovae observed in the past 25 years. This proximity allows for detailed observation and study, making SN2023ixf a crucial event for understanding core-collapse supernovae and their interactions with the surrounding environment.

2.1 Classification as a Type IIL Supernova

SN2023ixf has been classified as a Type IIL supernova. Type IIL supernovae are a subtype of Type II supernovae, which are characterized by the presence of hydrogen in their spectra. The "L" in IIL denotes a linear decline in the light curve after the peak brightness is reached, as opposed to the "P" in IIP supernovae, which have a plateau in their light curves.

In Type IIL supernovae, the progenitor star typically loses a significant amount of its hydrogen envelope before the explosion, leading to a relatively rapid decline in brightness as the hydrogen-rich outer layers are ejected. The study of SN2023ixf offers an opportunity to better understand the progenitor's mass-loss history and the physical conditions leading up to the supernova explosion.

2.2 Early Peak in the Light Curve

One of the most unusual and intriguing aspects of SN2023ixf is the very early time at which the peak of its light curve was observed. The light curve of a supernova represents the change in its brightness over time, and the peak indicates the point of maximum brightness. Typically, supernovae reach their peak brightness days to weeks after the initial explosion. However, SN2023ixf showed an unexpectedly early peak, suggesting a rapid release of energy and interaction with the surrounding material.

This early peak could indicate that the progenitor star had a dense circumstellar medium (CSM) close to its surface. The interaction between the supernova ejecta and this CSM would have led to the rapid conversion of kinetic energy into radiation, causing the early rise in brightness. This phenomenon is critical for understanding the immediate environment of the progenitor star and the nature of its mass-loss process in the years leading up to the explosion.

2.3 Probing Supernova-CSM Interaction

The interaction between supernova ejecta and the circumstellar medium (CSM) is a key area of study in modern astrophysics. SN2023ixf provides a valuable probe for this interaction, especially due to its proximity, which allows for high-resolution observations.

When the supernova ejecta collide with the CSM, shock waves are generated, which can produce additional radiation and significantly alter the light curve. This interaction can also lead to the formation of X-ray and radio emissions, which are detectable with modern telescopes. By studying these emissions from SN2023ixf, astronomers can gain insights into the density, composition, and extent of the CSM, as well as the velocity and energy of the supernova ejecta.

Additionally, the study of the supernova-CSM interaction in SN2023ixf can provide information about the progenitor star's mass-loss rate in its final stages. Understanding this process is crucial for developing models of stellar evolution, particularly for massive stars, and for predicting the outcomes of other similar supernovae.

2.4 Significance of SN2023ixf in Supernova Research

SN2023ixf is a landmark event in the study of supernovae for several reasons. Its classification as a Type IIL supernova, combined with its proximity and unusual light curve characteristics, offers a rare opportunity to study the detailed physics of supernova explosions and their environments. The early peak in the light curve, in particular, challenges existing models of supernova behavior and highlights the need for further research into the interactions between supernovae and their circumstellar environments.

Moreover, the data gathered from SN2023ixf will contribute to the broader understanding of core-collapse supernovae, the end stages of massive stars, and the role these events play in enriching the interstellar medium with heavy elements. As one of the closest observed supernovae in recent history, SN2023ixf will likely serve as a reference point for future studies and continue to provide valuable insights into the life cycles of stars and the dynamic processes that shape our universe.

3 Introduction to project

Over the course of this project, we analyzed the supernova SN2023ixf. The data for this was provided by our mentors, and we conducted detailed research on it.

4 CCD Detectors

4.1 What are CCD Detectors

CCD detectors (Charge-Coupled Devices) convert light into electronic signals, enabling detailed, high-resolution images. In astronomy, they are crucial for capturing clear images of celestial objects, allowing for precise measurements of stars, galaxies, and distant phenomena, thus enhancing our understanding of the universe.

4.2 Structure

The structure of CCDs (Charge-Coupled Devices) consists of several key components:

- **Silicon Substrate:** The base material of the CCD, typically made of silicon, which is sensitive to light.
- **2D Array of Pixels:** An organized grid of photodiodes, where each photodiode corresponds to a single pixel. This array captures the image.
- **Quantum Efficiency (QE):** A CCD detects individual photons, but even the best CCD does not detect every single photon that falls on it. The fraction of photons falling on a CCD that are actually detected by the CCD is called the quantum efficiency (QE), usually expressed as a percentage.
- **Cooling Systems:** Astronomical CCDs are often cooled to very low temperatures using liquid nitrogen or thermoelectric coolers. Cooling reduces thermal noise significantly, allowing for longer exposure times and the detection of faint signals.
- **Long Exposure Time:** Astronomical observations often require long exposure times to collect enough light from distant objects. CCDs can accumulate charge over extended periods, allowing astronomers to detect faint celestial bodies that are not visible in shorter exposures.
- **Spectroscopy:** CCDs are not only used for imaging but also for spectroscopy in astronomy. When combined with a spectrograph, CCDs can capture the spectrum of light from celestial objects, providing valuable information about their composition, temperature, velocity, and other physical properties.

4.3 Applications in Astronomy

- **Spectroscopy:** When combined with a spectrograph, CCDs can capture the spectrum of light from celestial objects, providing valuable information about their composition, temperature, velocity, and other physical properties.
- **Deep-Sky Imaging:** Capturing detailed images of galaxies, nebulae, star clusters, and other deep-sky objects.
- **Planetary Imaging:** We can observe planets and their motion using CCD detectors.

5 Image Reduction

In astronomical data analysis, refining images is crucial to ensure accurate and reliable results. This process involves several steps to process raw images captured by CCD detectors, aiming to eliminate noise, correct for instrumental discrepancies, and enhance data quality. The ultimate goal is to produce scientifically reliable images that accurately represent celestial bodies.

5.1 GIT (Growth India Telescope)

The Growth India Telescope (GIT) is a significant observational facility designed to capture high-quality astronomical images and data. It is equipped with advanced imaging systems and photometric filters that enhance its observational capabilities.

5.1.1 Photometric Filter Sets

Photometric filters are essential tools in astronomy for isolating specific passbands of light, enabling precise measurements of celestial objects. They allow astronomers to analyze different wavelengths of light, which provides insights into various properties of the objects being studied.

Types of Photometric Filters

- **Narrow-band Filters:** These filters isolate a very narrow range of wavelengths, allowing for the study of specific emission or absorption lines in astronomical objects.
- **Broadband Filters:** These filters cover a wider range of wavelengths and are used to capture broader spectral features. They are useful for general imaging and studying the overall characteristics of celestial objects.

Common Photometric Systems

- **UBVRI System:** This system includes filters for ultraviolet (U), blue (B), visual (V), red (R), and infrared (I) bands.
- **UGRIZ System:** Commonly used in modern astronomical surveys, this system includes filters for ultraviolet (U), green (G), red (R), infrared (I), and z-band (Z).
- **JHK System:** This system includes filters for near-infrared bands J, H, and K.

GIT Filter Set The GIT uses the SDSS UGRIZ filters, which are broadband filters covering a range of 100 nm. This filter set provides comprehensive coverage of the optical spectrum, allowing for detailed analysis of astronomical objects across multiple wavelengths.

5.2 Detectors and Sensors

Detectors and sensors are crucial components of astronomical telescopes, located in the focal plane where they record incident photons. They are typically made up of 2D pixel arrays that convert light into electronic signals.

Types of Detectors

- **CCD (Charge-Coupled Device):** CCDs are highly sensitive to light and are widely used in astronomy for their excellent imaging capabilities and low noise characteristics.
- **CMOS (Complementary Metal-Oxide-Semiconductor):** CMOS sensors are known for their high-speed readout and lower power consumption compared to CCDs.

GIT Sensors The GIT employs SBIG and ANDOR CCD sensor cameras, which are renowned for their high sensitivity and precise imaging capabilities. These sensors are essential for capturing detailed and accurate astronomical data.

5.3 Raw Image

The raw image is the initial output from the CCD detector. This image is often contaminated with various types of noise and artifacts that can obscure the true signal from celestial objects. Raw images need extensive processing to mitigate these issues and reveal clear astronomical data.

5.4 Types of Noise

In astronomical imaging, several types of noise can affect the quality of raw images:

- **Bias Level:** This refers to the electronic offset added to the signal in each pixel to prevent negative values. Bias level noise is inherent to the CCD sensor and must be accounted for during the processing phase.
- **Dark Current:** Dark current is thermal noise generated by the CCD even in the absence of light. It results from the thermal excitation of electrons within the CCD and contributes to background noise in the images.
- **Flat Field Variations:** These variations occur due to differences in pixel sensitivity and optical distortions across the imaging field. They cause uneven illumination and must be corrected to achieve uniform image quality.
- **Cosmic Rays:** High-energy particles from space can strike the CCD, creating bright spots or streaks in the images. These cosmic rays can significantly affect image quality and must be removed to ensure accurate data analysis.

5.5 Image Reduction Process

The image reduction process involves several key steps to address and correct the various types of noise and artifacts in the raw images:

5.5.1 Bias Correction

Bias correction is performed to remove the electronic offset from the CCD. This is achieved by taking images with a short exposure time and with the shutter closed, which captures only the bias level. The average bias frame, representing the electronic offset, is then subtracted from the raw images to eliminate the bias noise.

5.5.2 Dark Current Correction

To correct for dark current, long exposure images are taken with the shutter closed. These images capture the thermal noise generated by the CCD. The average dark frame, which represents the dark current, is then subtracted from the bias-corrected images to remove this source of noise.

5.5.3 Flat Field Correction

Flat field correction addresses variations in pixel sensitivity and optical distortions. This is done by capturing images of a uniformly illuminated source, such as a twilight sky or a specially designed flat-field screen. The resulting flat field frame is normalized and used to divide the bias and dark-corrected images, thereby correcting for variations in pixel sensitivity and optical distortions.

5.5.4 Cosmic Ray Removal

To address cosmic rays, we first detect them using specialized algorithms that identify outliers or through median combining of multiple exposures of the same field. The algorithms mark the regions affected by cosmic rays, allowing for their removal or correction. This step helps to eliminate the bright spots or streaks caused by high-energy particles, improving the overall quality of the images.

6 Image Reduction (Coding)

The coding aspect of the image reduction process is detailed in the notebook 'image_reduction.ipynb'. This notebook includes the implementation of image reduction specifically for the g-band data. The following points summarize the coding process and its context:

- **Notebook Overview:** The notebook 'image_reduction.ipynb' contains Python code that performs the image reduction steps for the g-band data. This includes bias correction, dark current correction, flat field correction, and cosmic ray removal.
- **Data Processing:** For the g-band data, the raw images are processed through the specified reduction steps to eliminate noise and improve image quality.
- **Pre-processed Data:** For other bands, we were provided with pre-processed, image-reduced files. Thus, the image reduction process was only applied to the g-band data in our case.

For detailed code and implementation, refer to the 'image_reduction.ipynb' notebook.

7 Astrometry

Astrometry is the science of measuring the positions, motions, and distances of celestial objects with high precision. It plays a crucial role in understanding the spatial relationships and movements of stars, planets, and other astronomical bodies. The process involves converting image coordinates into a standardized world coordinate system (WCS), which allows for accurate astronomical measurements and comparisons.

7.1 Theory of Astrometry

The primary goal of astrometry is to accurately measure the positions and movements of celestial objects. This involves several key aspects:

- **Star Detection:** The first step in astrometry is detecting stars within an image. This typically involves identifying the locations of stars based on their brightness and distribution within the field of view.
- **Pattern Matching:** Once stars are detected, their positions are matched against known star patterns or catalogs. This helps in identifying and confirming the stars' positions and ensuring the accuracy of the measurements.
- **Calibration:** Calibration is essential to account for systematic errors and distortions in the image. It involves adjusting the measurement system to ensure that the coordinates are accurately mapped to the celestial coordinate system.
- **Positional Accuracy:** Achieving high positional accuracy involves correcting for various sources of error, including instrumental effects, atmospheric distortions, and geometric distortions.

The conversion from the x and y pixel coordinate system used in images to the world coordinate system (WCS) allows for consistent and accurate astronomical measurements. The WCS provides a standardized framework for expressing the positions of celestial objects in terms of right ascension and declination.

7.2 Implementation Using nova.astrometry.net

In this project, astrometry was performed using the online tool nova.astrometry.net. The steps involved in this process are outlined below:

- **Data Preparation:** After completing the image reduction, we had 30 processed files. A subset of 5 files was selected for astrometric analysis.
- **Astrometric Analysis:** The selected files were uploaded to nova.astrometry.net, which provided astronomical reference for the stars in the images. This tool helps in aligning the image coordinates with the world coordinate system.
- **Obtaining WCS and COR Files:** After processing the images, nova.astrometry.net generates two important files:
  - **wcs.fits:** This file contains the world coordinate system information, mapping the image coordinates to celestial coordinates.
  - **cors.fits:** This file includes additional correction parameters and is used for further processing and analysis.
- **Task1.1 Implementation:** The code for Task1.1 was executed using the obtained 'wcs.fits' and 'cors.fits' files. Details of this implementation for one of the files can be found in Task1.1 on my GitHub repository.

8 Photometry

After obtaining the `wcs.fits` and `cors.fits` files from the astrometry process, the next step in our analysis is photometry. Photometry involves measuring the brightness of celestial objects in the images. By analyzing the intensity of light received from stars or other astronomical objects, we can derive valuable information about their properties and behaviors.

8.1 What is Photometry?

Photometry is the science of measuring the intensity of light from astronomical objects. This measurement is typically quantified as the brightness or flux of the object. In practical terms, photometry helps us calculate the apparent magnitude of stars, galaxies, or other celestial bodies, which is a measure of how bright these objects appear from Earth.

8.2 How Does Photometry Help Us?

Photometry plays a crucial role in a wide range of astronomical studies:

- **Instrumental Magnitude:** Photometry allows us to calculate the instrumental magnitude of stars. This is an initial estimate of the star's brightness as recorded by the detector, before any calibration or correction is applied.
- **Light-Curves:** By performing photometry on a series of images taken over time, we can plot light-curves, which show how the brightness of an object changes over time. Light-curves are essential for studying variable stars, eclipsing binaries, and other time-dependent phenomena in astronomy.

- **Stellar Evolution:** Photometry helps uncover the processes of stellar evolution. By analyzing the brightness of stars at different stages of their lifecycle, astronomers can infer details about their age, mass, and the nuclear processes occurring within them.

8.3 Types of Photometry

There are two main types of photometry used in astronomy:

8.3.1 Aperture Photometry

Aperture photometry is the simplest and most commonly used method. In this technique, the brightness of a star is measured by summing the light within a defined circular aperture centered on the star. The background light, which comes from the sky and other sources, is also measured and subtracted from the total light to obtain the star's net brightness.

- **Procedure:** A circular aperture is placed over the star in the image, and the total flux within this aperture is calculated. A separate region, usually an annulus around the star, is used to estimate the background flux, which is then subtracted from the total flux.
- **Advantages:** Aperture photometry is straightforward and works well for isolated stars or when the star's light is not contaminated by nearby objects.
- **Disadvantages:** This method can be less accurate in crowded fields or when the stars are close together, as it may be challenging to separate the light from neighboring objects.

8.3.2 PSF Photometry

PSF (Point Spread Function) photometry is a more sophisticated method, particularly useful in crowded star fields or when dealing with overlapping objects. The PSF describes the response of the imaging system to a point source, such as a star.

- **Procedure:** In PSF photometry, the observed star's brightness is modeled by fitting a PSF to the star's image. This involves adjusting the PSF's parameters to match the observed star's profile, allowing for more accurate measurement of its flux, especially in crowded fields.
- **Advantages:** PSF photometry is highly accurate in complex fields, where stars are close together, or when precise measurements are needed.
- **Disadvantages:** It is more computationally intensive and requires a good understanding of the PSF, which may vary across the image due to instrumental or atmospheric effects.

8.4 Photometric Analysis Using `wcs.fits` and `cors.fits`

In our project, after obtaining the `wcs.fits` and `cors.fits` files from astrometry, we performed photometric analysis on the images. The WCS information was crucial for accurately identifying and measuring the stars in the images, allowing us to convert pixel coordinates to celestial coordinates.

By applying both aperture and PSF photometry techniques, we were able to extract detailed brightness measurements of the stars. These measurements will be used to generate light-curves and analyze the stellar properties, contributing to our understanding of the stars' behavior and evolution.

This photometric analysis is a key component of our overall study, providing the quantitative data needed for further astrophysical interpretation.

9 Aperture Photometry

Aperture photometry is a fundamental technique used in the analysis of astronomical images, particularly for measuring the brightness of point-like sources such as stars. This method involves defining a circular aperture around the object of interest and summing the pixel values within this aperture to estimate the total flux from the object.

9.1 Key Features of Aperture Photometry

- **Total Flux Measurement:** Aperture photometry measures the total flux within a defined aperture around the object, which is essential for calculating the object's brightness.
- **Ideal for Isolated Sources:** This technique is best suited for isolated, point-like sources, such as individual stars, where there is minimal contamination from neighboring objects.
- **Low Computational Requirement:** Aperture photometry is computationally less intensive compared to more advanced techniques like PSF photometry, making it an efficient choice for quick analysis.

9.2 Aperture Photometry Tool (APT)

The Aperture Photometry Tool (APT) is a widely-used software application designed for performing aperture photometry on astronomical images. APT offers a user-friendly interface and a range of features that make it a valuable tool for astronomers.

- **User Interface:** APT provides an intuitive graphical user interface (GUI) that allows users to visually select apertures and background regions directly on the image. This makes the process of performing photometry straightforward and accessible, even for those with limited programming experience.
- **Customization:** Users can customize the size and shape of the apertures, as well as the background regions, to suit their specific needs. APT also supports batch processing, enabling photometry to be performed on multiple images simultaneously.
- **Output:** The tool generates detailed reports that include the measured fluxes, uncertainties, and other relevant parameters. These reports can be easily exported for further analysis or integration into larger datasets.
- **Integration with Other Software:** APT can be used in conjunction with other astronomical software, making it a flexible tool that can be integrated into various workflows.

9.3 Photutils: SkyCircularAperture

Photutils is a Python library that provides tools for performing photometry and other image analysis tasks in astronomy. One of its key features is the `SkyCircularAperture` class, which is used for defining and applying circular apertures in celestial coordinates.

- **SkyCircularAperture:** This class allows for the creation of circular apertures based on the sky coordinates (right ascension and declination) of the target objects. It is particularly useful when working with images that have World Coordinate System (WCS) information, enabling accurate placement of apertures on celestial objects.
- **Application:** `SkyCircularAperture` can be used in a variety of photometric tasks, including the measurement of fluxes from stars and other point sources. By defining apertures in sky coordinates, it ensures that the measurements are consistent across different images and observation sessions.

- **Integration with Photutils:** Photutils provides additional functionality, such as background subtraction and error estimation, which can be easily combined with `SkyCircularAperture` to perform comprehensive photometric analysis.

Aperture photometry, whether conducted using tools like APT or libraries like Photutils, remains a cornerstone technique in astronomical data analysis. It provides a robust method for measuring the brightness of celestial objects, particularly in cases where the sources are well-isolated and point-like.

10 PSF Photometry

PSF (Point Spread Function) photometry is an advanced technique used to accurately measure the flux of stars or other celestial objects, especially in crowded fields where sources may overlap. Unlike aperture photometry, which sums pixel values within a fixed aperture, PSF photometry uses a model of the star's image on the detector to weigh pixel values based on the expected distribution of light.

10.1 What is PSF Photometry?

PSF photometry involves creating a small cutout around the source, subtracting the background, and summing the counts using the PSF model as a weight. This method provides a more precise measurement of a star's flux, especially in situations where stars are close together or blended.

Key steps include:

- **Small Cutout around the Source:** A small region around the star is extracted to focus on the area of interest.
- **Background Subtraction:** The background level is subtracted to isolate the star's flux.
- **Instrumental Magnitude (Ins_mag):** The sum of all the counts is calculated using the PSF model as a weight, which provides the instrumental magnitude.

Packages: The primary packages used for PSF photometry are `SExtractor` and `PSFEx`.

10.2 Why is PSF Photometry Important?

PSF photometry is crucial in crowded fields, where multiple sources may overlap. By fitting a model to each star's image, it allows for accurate flux measurements even when sources are not well-separated. The components and characteristics of the PSF are vital for understanding how light is distributed across the detector, and this understanding enables precise measurements of star brightness and positions.

10.3 Photometry Using SExtractor

`SExtractor` is a widely-used algorithm for source extraction and photometry. It works by detecting and cataloging sources in astronomical images, and then measuring their fluxes.

The key steps in using `SExtractor` for photometry include:

- **Reading the FITS File:** The FITS file containing the astronomical data is read and processed.
- **WCS Transformation:** World Coordinate System (WCS) information is used to map pixel coordinates to celestial coordinates.
- **Catalog Query and Processing:** A catalog of detected sources is created and processed for further analysis.

- **Source Extraction:** The algorithm identifies and extracts sources from the image.
- **Cross Matching:** Extracted sources are cross-matched with known catalogs to identify and measure objects.

This was not that usefull as we were getting high error bars and was not working good for i,r band . An image illustration for photometry using sextractor is shown here for g band. Ultimately we prefered psf fit over it.

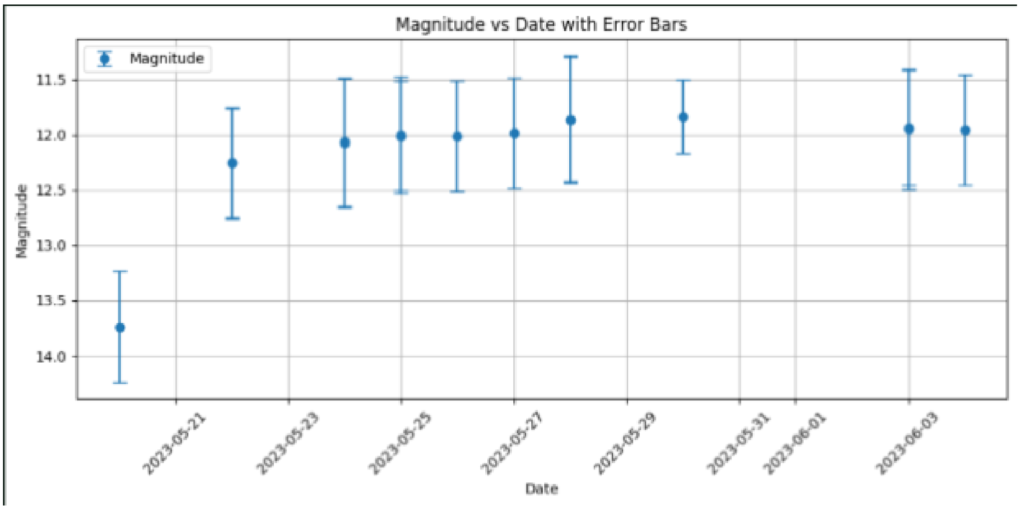

Figure 1: Photometry using sextractor for g-band

10.4 Photometry Using PSF Fit

`PSFEx` is another method that focuses on fitting a PSF model to each detected source to measure its flux more accurately. The steps involved in PSF fit photometry are:

- **Preparation:** The image is prepared by preprocessing, including background subtraction and noise reduction.
- **Extract and Normalize the PSF Data:** A PSF model is extracted from the image and normalized to serve as a template for fitting.
- **Fit the PSF to a Star:** The PSF model is fitted to each detected star to measure its flux.
- **Align the PSF with the Star:** The PSF model is aligned with the star's position in the image.
- **Output Generation:** The results, including flux measurements and positional information, are generated and saved for further analysis.

10.5 Implementation and Challenges

This method of PSF photometry has been successfully implemented for the **g**, **i**, and **r** bands. However, the **u** band presented challenges due to its lower signal-to-noise ratio and higher susceptibility to atmospheric effects. As a result, accurate photometry for the **u** band was more difficult to achieve, leading to incomplete data for this band.

11 U-band Photometry

11.1 Challenges in U-band Photometry

- U-band photometry, focusing on the ultraviolet (UV) spectrum, is particularly challenging due to atmospheric absorption and scattering.
- The Earth's atmosphere significantly reduces the amount of UV light reaching ground-based telescopes, leading to darker images and lower signal-to-noise ratios.
- These atmospheric effects make it difficult to detect and accurately measure celestial objects in the U-band.
- Figure 2 illustrates the difficulty in star detection due to the faintness of U-band observations.

11.2 Process Overview

1. Initialization and PSF Data Extraction:

- `SExtractor` is used for the initial detection of stars in U-band images.
- This involves scanning the image for point sources, using pixel intensity thresholds to identify potential stars.
- Once stars are detected, their X, Y coordinates are extracted for further analysis.
- PSF (Point Spread Function) fitting is then applied to these detected stars to calculate their instrumental magnitudes.
- The PSF model is used to fit the detected stars, which allows for an accurate measurement of their brightness before calibration.
- The same algorithm is employed as in g, i, and r bands, with modifications to account for the lower signal levels in U-band data.

2. Calibration and Finding Constant Stars:

- Calibration is essential to convert instrumental magnitudes into accurate photometric measurements.
- **Offset Plots:**
  - Offset plots are used to identify constant stars, which are stars that show consistent brightness over time.
  - Each star's brightness is compared to its catalog value, and stars with significant deviations (outliers) are excluded from the calibration process.
  - The median and standard deviation of the remaining stars' offsets are calculated to determine the photometric zero point and estimate measurement errors.
- **Relative Photometry:**
  - Involves comparing the brightness of stars over time to identify those with stable magnitudes.
  - Stable stars are ideal for calibration as their consistent brightness helps in accurately determining the zero point.
  - Figure 3 shows a plot of magnitude corrections (magcor) over time for selected stars, with consistent magcor values indicating stable stars.

11.3 Challenges and Future Refinements

- Despite rigorous calibration methods, U-band data often show deviations compared to other bands, indicating the need for further refinement in star selection and calibration techniques.
- The inherent challenges of lower signal-to-noise ratios and greater atmospheric interference in the U-band require more sophisticated approaches to achieve precision comparable to other photometric bands.
- Future work will focus on improving the criteria for selecting calibration stars and exploring alternative methods for atmospheric correction.

11.4 Current Status

- The described methodology has been successfully implemented for the g, i, and r bands, resulting in reliable photometric measurements.
- U-band photometry remains challenging, and while some progress has been made, further refinements are necessary to achieve the desired accuracy.

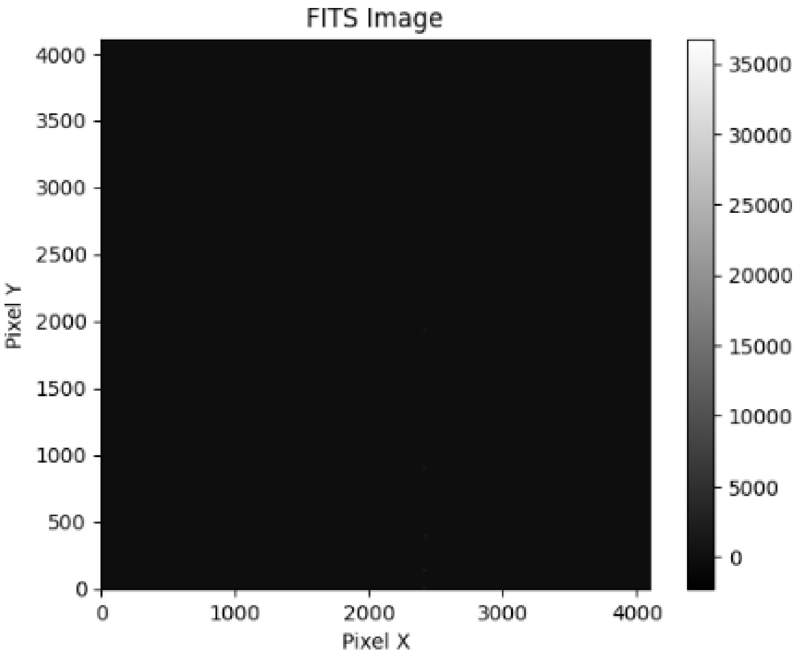

Figure 2: U-band image showing the difficulty of star detection due to the dark background and low signal levels.

12 Coding Implementation of Photometry

All the methods discussed above—aperture photometry, PSF photometry, and calibration techniques—were implemented in code to analyze the g, i, r, and u bands. The detailed code and scripts used for these implementations can be found in my GitHub repository. The repository is organized into separate folders for each band, with the relevant scripts and data processing steps clearly documented.

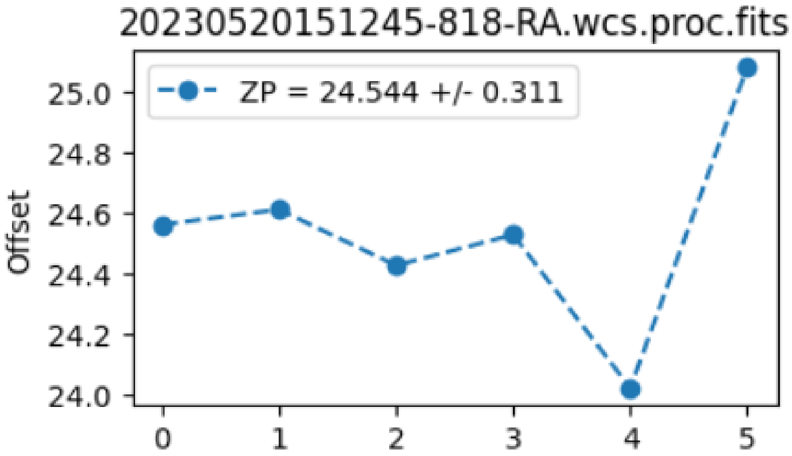

Figure 3: Relative photometry plot showing magnitude corrections of stars over time, highlighting the stability of selected calibration stars.

12.1 GitHub Repository Structure

The GitHub repository is structured as follows:

- **g-band Photometry:**
  - Contains scripts for data reduction, aperture photometry, PSF photometry, and calibration for the g-band.
  - Includes offset plots and relative photometry analysis for calibration stars.
- **i-band Photometry:**
  - Similar structure as the g-band folder, with scripts tailored for i-band data.
  - Detailed documentation on the calibration process and star selection criteria.
- **r-band Photometry:**
  - Scripts for data reduction, photometry, and calibration specific to r-band observations.
  - Includes plots and graphs demonstrating the results of the photometric analysis.
- **u-band Photometry:**
  - Focuses on the unique challenges of u-band photometry.
  - Contains scripts for initial star detection using `SExtractor`, PSF fitting, and calibration.
  - Includes offset plots and relative photometry analysis to identify stable calibration stars.

12.2 Summary of Code Functionality

- The code automates the process of data reduction, star detection, and photometric measurement across different bands.
- It includes functions for extracting PSF data, fitting PSF models to stars, and calculating instrumental magnitudes.
- Calibration scripts adjust the instrumental magnitudes to account for atmospheric and instrumental effects, ensuring accurate photometric measurements.

- The code also generates plots for offset analysis and relative photometry, aiding in the identification of stable calibration stars.

12.3 Final Light Curve

The culmination of these efforts is the generation of the final light curve, which provides a comprehensive view of the brightness variations of the observed stars over time. This light curve is crucial for subsequent modeling and analysis to understand the properties and behavior of the celestial objects studied.

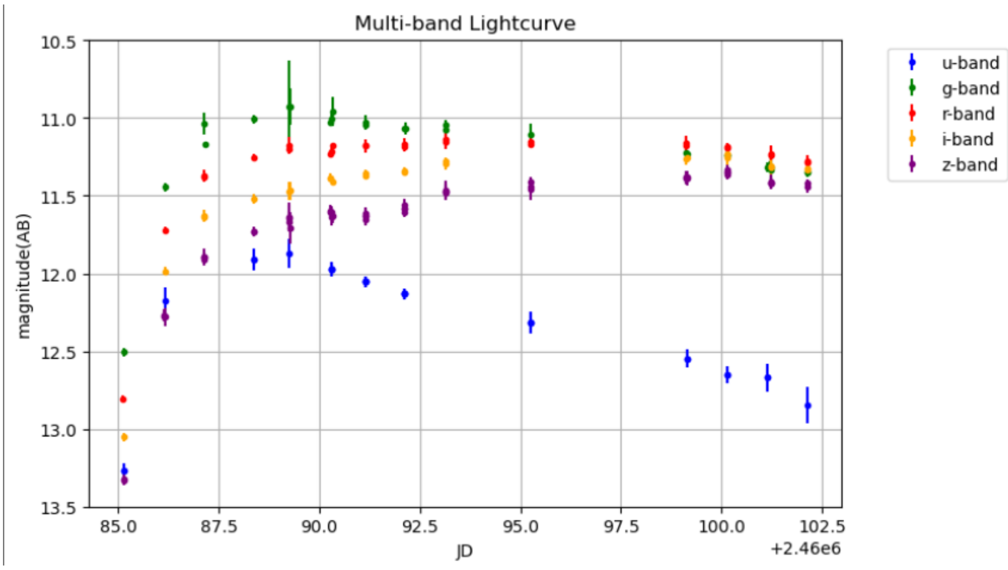

Figure 4: Final light curve showing the brightness variations of observed stars over time, compiled from the g, i, r, and u band data.

The final light curve, compiled from the g, i, r, and u band data, is attached to this report. It represents the culmination of the photometric analysis and provides the basis for further modeling and interpretation of the astrophysical phenomena under study.

13 Modeling the Supernova Progenitor

13.1 Introduction to the Purpose of Image Reduction and Photometry

After going through the intricate processes of image reduction, photometry across different bands, and all associated complex procedures, one might wonder about the purpose of these steps. Why is it essential to perform these detailed analyses? The answer lies in the ultimate goal: to derive critical parameters of the progenitor of the supernova (SN). The observed light curves, particularly in the U-band, serve as a fundamental tool for this purpose. However, as previously mentioned, U-band photometry is significantly influenced by atmospheric conditions, necessitating corrections for the black body spectrum to ensure accurate analysis.

13.2 Utilizing SuperBol for Parameter Estimation

To achieve these corrections and proceed with accurate modeling, we employed the `SuperBol` package. This tool is specifically designed for analyzing supernova light curves and estimating key parameters crucial for understanding the supernova's properties.

SuperBol allows us to estimate parameters such as:

- Bolometric luminosity
- Temperature evolution
- Radius expansion

By applying SuperBol, we derived the black body corrected luminosity, which provides a more accurate representation of the supernova's energy output. This step is crucial for obtaining reliable estimates of the supernova's characteristics, free from the distortions caused by atmospheric effects.

13.3 Curve Fitting Using a Luminosity Model

After obtaining the corrected magnitudes from SuperBol, the next step was fitting a curve to this data. We utilized a specific luminosity model described in Section 3.1 of a research paper, which incorporates the decay of radioactive Nickel-56 (^{56}Ni) and Cobalt-56 (^{56}Co). These isotopes are critical for powering the supernova's light curve.

The fitted curve, which models the light curve behavior over time, looks like this (see Figure **??**). This curve is instrumental in understanding the temporal evolution of the supernova's brightness and provides insight into the underlying physical processes.

13.4 Estimating Nickel-56 Mass and Characteristic Time

From the fitted curve, we can estimate the mass of ^{56}Ni by analyzing the model's parameters. The luminosity function of the supernova is directly related to the characteristic time—a period of rapid brightening followed by a slow dimming. The slope of the plot is indicative of the mass (M), while the intercept corresponds to the characteristic time (t_c).

Our estimated value for the mass of ^{56}Ni is ______. This estimation is based on the assumption that after 90 days, the light curve is primarily influenced by the decay of ^{56}Ni, which dominates the energy output at this stage of the supernova's evolution.

13.5 Calculating Ejecta Masses and Explosion Energies

With the mass of ^{56}Ni and the time of explosion estimated, the next step is to calculate the explosion energy (E_{51}) and ejecta mass (M_{10}). These parameters are vital for understanding the dynamics and scale of the supernova explosion, as well as the nature of the progenitor star.

The calculations for E_{51} and M_{10} are based on equations provided in Appendix C of a detailed study. These calculations consider different progenitor radii to estimate plausible ranges for the ejecta masses and explosion energies.

Through this analysis, we have been able to estimate:

- Ejecta masses (M_{10})
- Explosion energies (E_{51})

These estimations are crucial for modeling the supernova and understanding the physical properties of the progenitor star, which ultimately helps in understanding the dynamics and scale of the explosion.

13.6 Conclusion

In conclusion, the modeling part of our analysis is essential for deriving critical parameters of the supernova, such as the mass of ^{56}Ni, the explosion energy, and the ejecta mass. These parameters are key to understanding the dynamics of the explosion and the nature of the progenitor star. Despite the challenges posed by U-band photometry, particularly due to atmospheric conditions, the corrections applied and the modeling techniques used have allowed us to gain valuable insights into the supernova's characteristics.

14 Conclusion

This report presented a detailed study of the nearest hydrogen-rich core-collapse supernova, SN2023ixf, using data obtained from the Growth India Telescope (GIT). The process began with image reduction, followed by astrometry to reference the stars, and photometry across different bands (g, i, r, and u) to measure the brightness of celestial objects. U-band photometry posed unique challenges due to atmospheric interference, which were addressed through careful calibration and relative photometry.

The photometric data was then used to generate light curves, which are essential for understanding the properties and evolution of the supernova. Subsequent modeling with the SuperBol package allowed for the estimation of key parameters such as bolometric luminosity, temperature evolution, and the mass of radioactive Nickel-56, which powers the supernova's light curve.

All coding implementations for image reduction, photometry, and modeling are available in my GitHub repository at https://github.com/aditisingh1053/KSP2024-study-of-sn-2023ixf. The final light curve, derived from the analysis, provides a foundation for further study and interpretation of SN2023ixf.

This work not only contributes to our understanding of SN2023ixf but also demonstrates the application of advanced techniques in astrophysics, combining observational data with rigorous analysis and modeling.

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