KRITTIKA SUMMER PROJECTS 2024

Study of Nearest Hydrogen-rich Core collapse Supernova-SN2023ixf

Divyansh Tripathi

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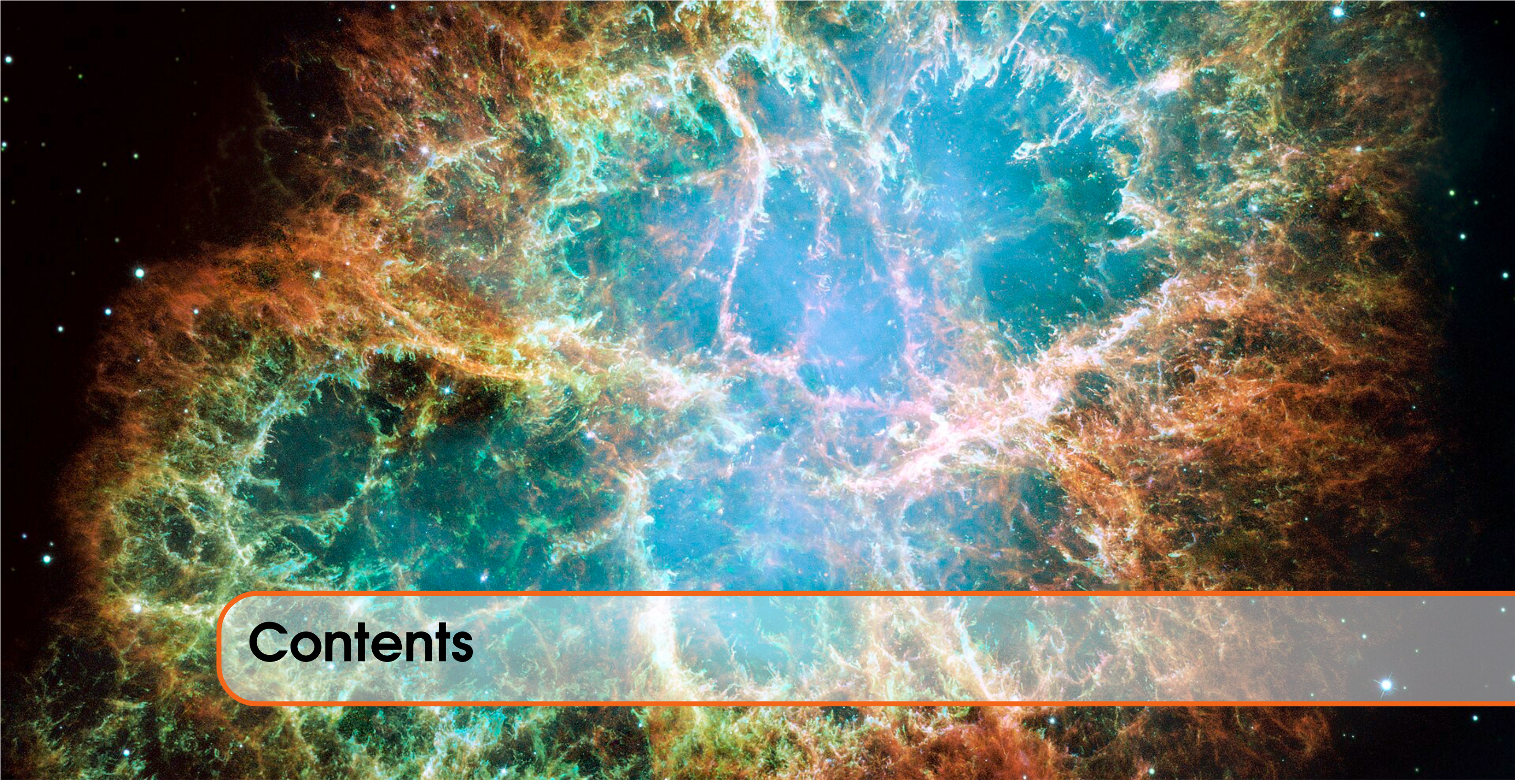
Abstract

In this project, I have analyzed SN2023ixf, the brightest supernova observed in the past 25 years. Throughout the project, I have gained skills in reducing images using Python libraries, performing astrometry on the reduced images, and conducting PSF photometry for the g, i, and r bands, as well as separate photometry for the u band data. Finally, I have plotted the light curve of the supernova across all observed wavelengths to track its intensity over approximately a month, and model it to know about luminosity and ejecta properties. .



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1. Introduction

1.1 Supernovae

Supernovae are the bright burst of energy and electromagnetic waves happen when a star of mass >8$M_\odot$ reaches the end of stellar evolution cycle and the core and no longer support the outer layers.
Star produce energy by fusing Hydrogen to helium and producing energy in the process, this energy and radiation holds the stars outer layers against the gravity, which tries to push it inwards.. Also as supplies of fuel is exhausted in the core, the fuel inside shells surrounding core gets burns and star reaches a stage known as **Schonberg Chandrasekhar Limit**, given by Kippenhahn, Weigert, and Weiss

$$\left(\frac{M_c}{M}\right) \approx 0.37 \left(\frac{\mu_c}{\mu_M}\right)$$

Star leaves main sequence and as the time progress hydrogen in the core gets depleted and star switches to fusing helium and eventually fusing elements like Carbon, Oxygen and Silicon. Eventually it reaches Iron(Fe), which can't be fused further and fusing it will require energy. Hence, no more energy production is possible. At some point of time iron core mass hits Chandrasekhar Limit (1.44$M_\odot$) and a runway mechanisms where core implodes and upper envelope falls back towards the centre and as the core hits nuclear saturation density, it can't be compressed further and it stalls creating a shock which fly away the downward moving core into a massive outflow, creating **Supernova** into its full glory.

1.2 Types of Supernovae

Supernovae are clasified into many types based on the elements present in their specturm and on how their lightcurve decay.

1. **Basis of Elements:**
    - **No H :** TypeIa

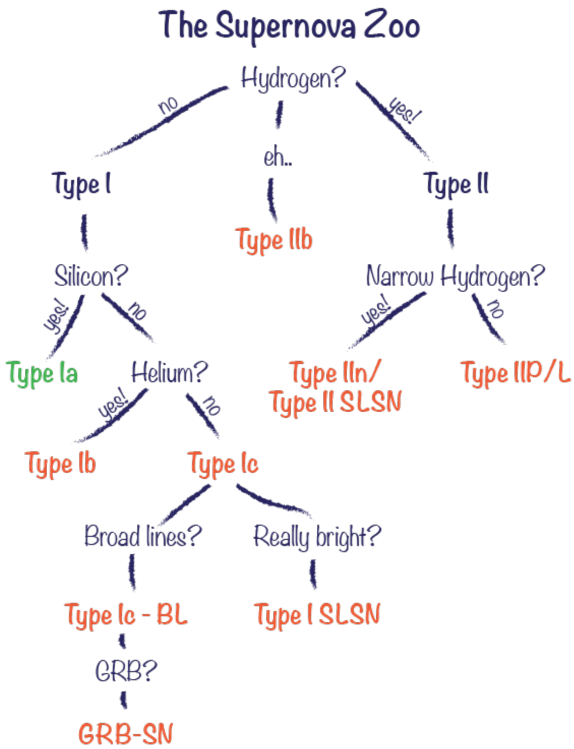


Figure 1.1: Credit: Astrobytes

- **With H** TypeIIa

2. **Based on Lightcurve Decay:**
   (a) **Linear Decay :** TypeIIL
   (b) **Plateau Decay :** TypeIIP

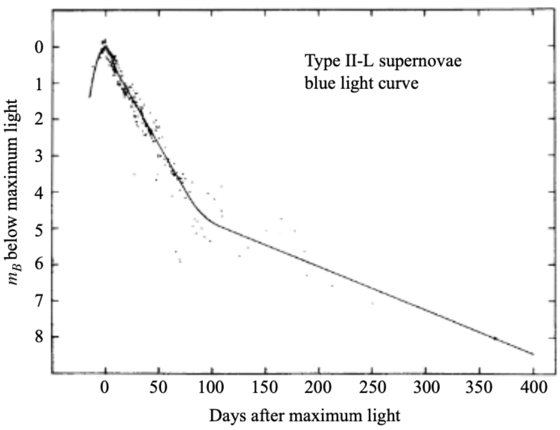


Figure 1.2: Lightcurve of TypeIIL

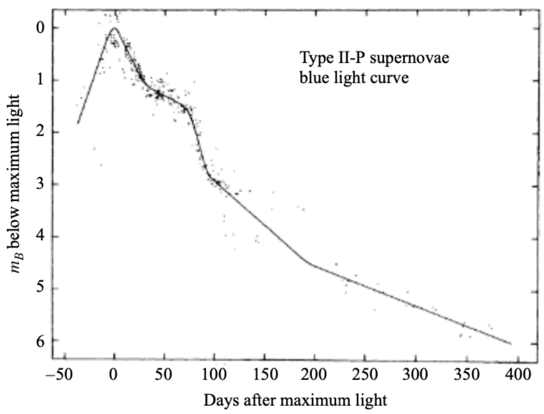


Figure 1.3: Lightcurve of TypeIIP

1.3 SN2023ixf

Discovered on 19^{th}May,2023 by Japanese amateur astronomer **Koichi Itagaki** in the galaxy M101 (Pinwheel Galaxy).
Classified as an TypeIIL supernova, it became the closest supernovae discovered in last 25 years.

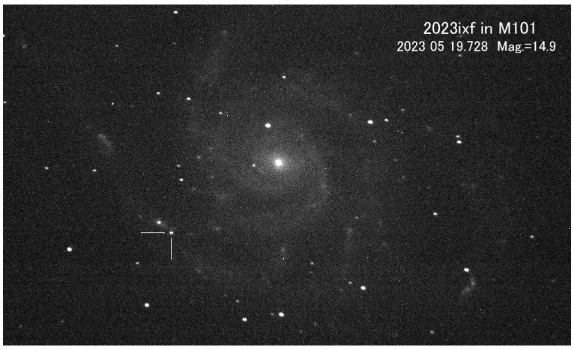


Figure 1.4: SN2023ixf (Credit: Koichi Itagaki

It was discovered in Messier 101 Galaxy at a distance of 6.9Mpc. The lightcurve of SN2023ixf peaked at 10.9mag at around 5 days, which is early for a TypeII supernovaes which generally peaked at around 10 days. This supernova provided

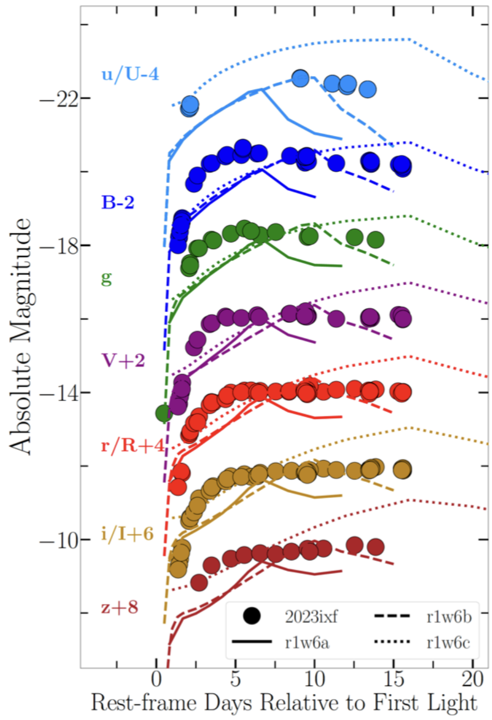
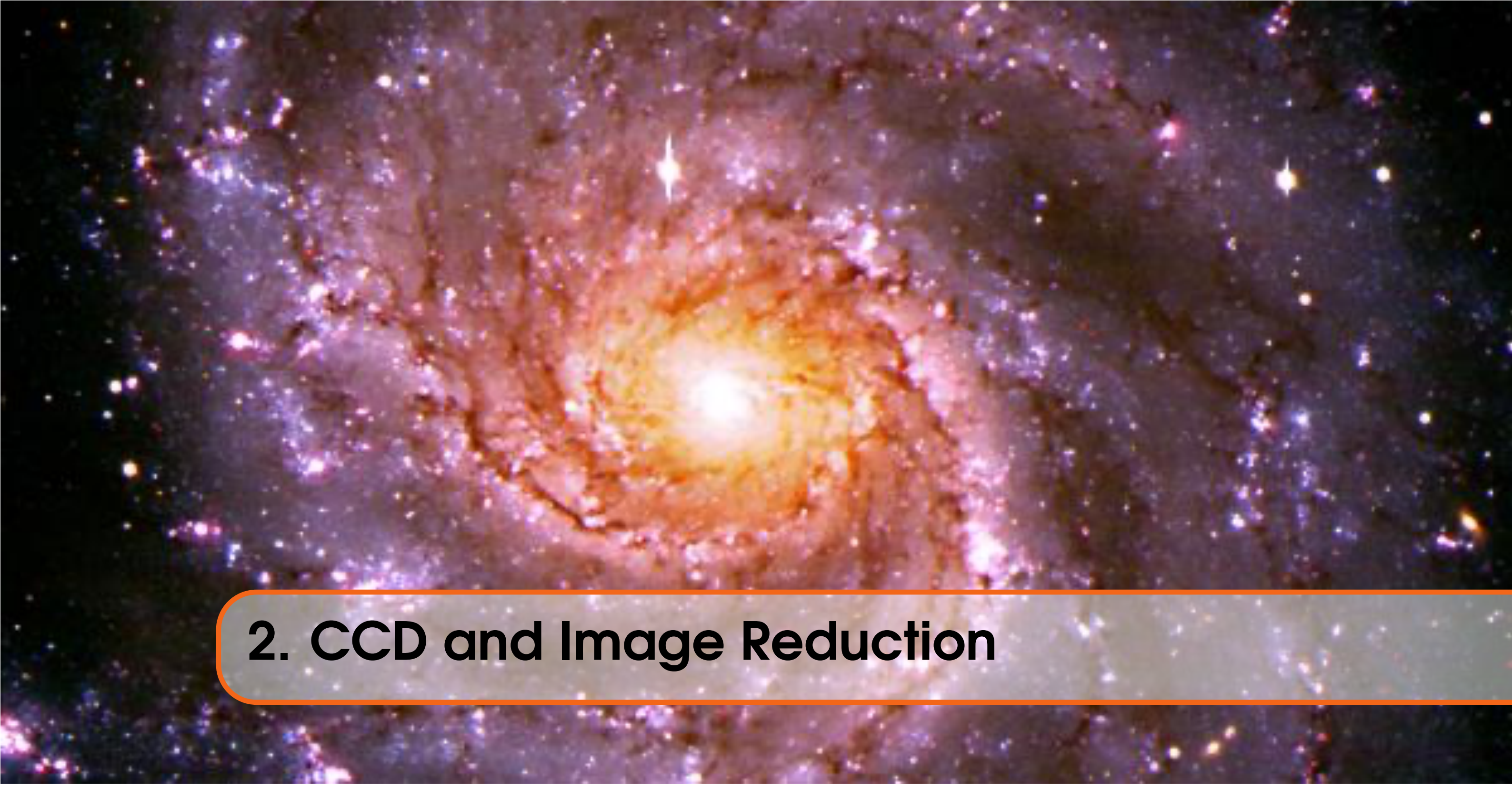


Figure 1.5: Lightcurve of SN2023ixf (Credit:arxiv:2306.04721)

an excellent oppurtunity to study properties of Core Collapse Supernova's and also how circumstellar medium interacts with supernovae and shocks and affects its luminosity as high amount of CSM is found near it.



2. CCD and Image Reduction

2.1 Astronomical Imaging and CCDs

The CCDs (Charge Couple Device) make the heart of today's astronomical telescopes. These chips works on the principle of photoelectrons, when light falls on a part of CCD, it release electrons. The no.of electrons released depend on type of electromagnetic wave that falls, and by reading it we can read the count on CCDs to extract the data. The no.of electrons released for 1 count is called the **gain** of the CCDs. Using gain and no.of electrons released we can get the count at every location of the image. These measurement are done using **ADC**(Analogue to Digital Converter) and the rate at which these reading are recorded is called the readout speed of the detector. This is a important factor in determining the SNR or quality of the image data.

2.2 Image Data Reduction

The process of removing noise and bias from the original data and get it ready for the scientific application is known as as Image Reduction. The Process following steps:

- Bias Subtraction
- Flat Fielding

2.2.1 Bias Subtraction

Often a bias voltage is applied to the detector to ensure some counts even in the absence of signal. A bias frame is created to measure the distribution of bias count over all the CCD fields and need to be subtracted during image analysis

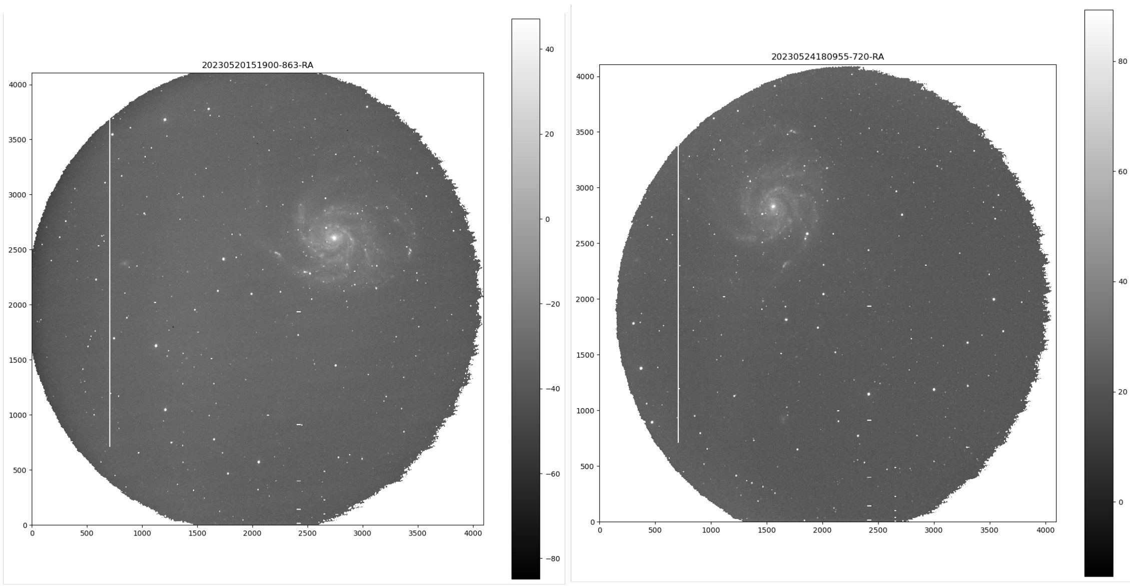
2.2.2 Flat Fielding

This measures the distribution of the pixels of the CCDs and how sensitivity they are. Flat frames are created by pointing the telescope to the uniform intensity light. These also need to be accounted. Bias subtraction is also done from the flat for as bias current is always there in the telescope. Now, The image recorded on the detector $\mathbf{I}(\mathbf{x},\mathbf{y})$ is a function of the true brightness distribution on the sky $\mathbf{S}(\mathbf{x},\mathbf{y})$ which is recorded in flat files and the response of the telescope optics and detector in different parts of the image $\mathbf{F}(\mathbf{x},\mathbf{y})$. with any bias signal added.
Hence,

$$\mathbf{I}(\mathbf{x},\mathbf{y}) = \mathbf{F}(\mathbf{x},\mathbf{y})\mathbf{S}(\mathbf{x},\mathbf{y}) + \mathbf{B}(\mathbf{x},\mathbf{y})$$

$$\mathbf{F}(\mathbf{x},\mathbf{y}) = \frac{\mathbf{I}(\mathbf{x},\mathbf{y}) - \mathbf{B}(\mathbf{x},\mathbf{y})}{\mathbf{S}(\mathbf{x},\mathbf{y})}$$

2.3 Image reduction Results



20230520151900-863 20230524180955-720

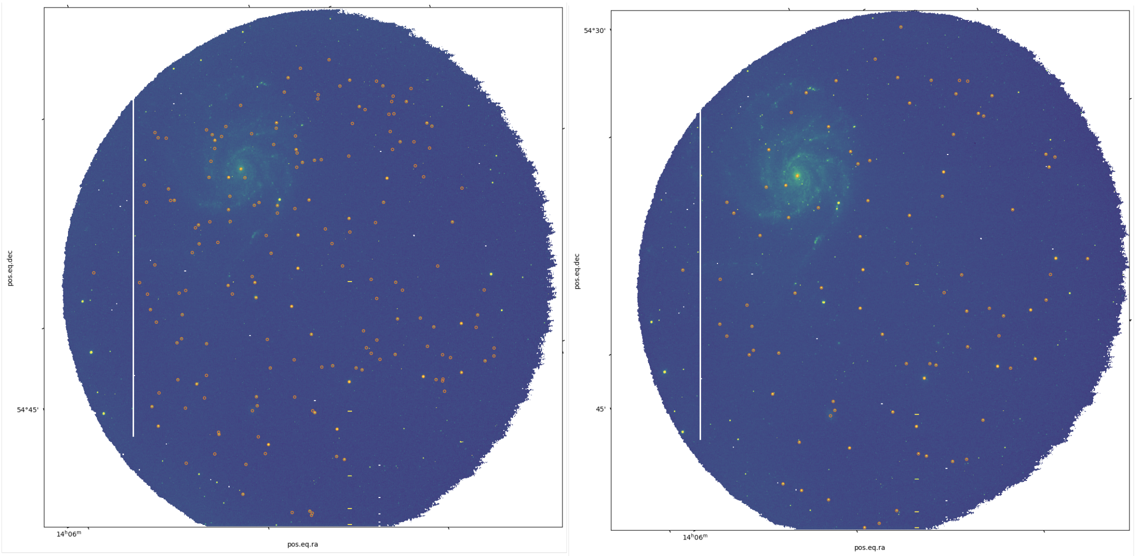
Figure 2.1: SN2023ixf Reduced g-band Data

3. Astrometry

3.1 Astrometry

t is the process of converting from the normal (x, y) coordinate system to (RA, Dec)coordinate system which is used of Sky observation in Astronomy. Here we have used astrometry.net(2), where we have uploaded the images and it gives us the file contains the transformation matrix to go form pixel coordinates to RA,Dec. It also gives the known stars that are found in your image on Cross-Matching with the catalog.

3.2 Astrometry Results

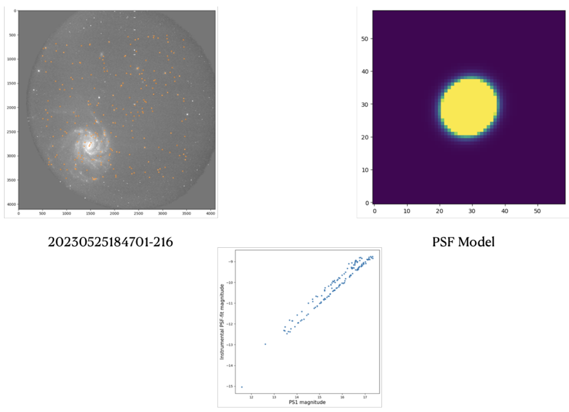


20230524180955-720 20230525184701-216

Figure 3.1: Astrometrically Corrected Imzge

4. Photometry

Photometry is the process of deriving the brightness of the interested object in the image. Since, when object imaging is done the brightness of our interested objects is contaminated by the background stars that is in our field of view and also due to instrument brightness. Here we are using PSF Photometry to derive the brightness of our object by creating a PSF model of the stars.
In PSF Photometry we compare a point spread type of function to each pixel of the image, this gives us if object located at each point of the image is a Point Source like stars or not. The PSF model creates a Moffat type function to fit on each star located in our image which we have found using the photometry. Each star is pixel is subtracte
We have done photometry on following g-band data of the SN-2023-ixf and found following magnitude of the source.



20230525184701-216

PSF Model

PSF Fit

Figure 4.1: 20230525184701-216

4.1 PSF-Fit Magnitude of different Bands

G-band Data

Date	Magnitude	e_magnitude	lim_mag
20230520151	13.342471384983600	0.018550758701033 00	19.087803244997000
20230521151	11.497471837556800	0.00180173742573858	16.37093573033800
20230521154	12.144546834107000	0.02552119475581990	19.693370891056800
20230522153	11.898321797790700	0.01819682052633020	19.300603483070900
20230522154	11.916896047910000	0.01904416514426020	19.657162517791300
20230523210	11.852625372842800	0.01986703563851840	19.41657454236640
20230524180	12.109664464688300	0.05376636625072610	18.635012414712100
20230524182	12.016114071624800	0.0588127920487066	18.683004282228800
20230525184	11.824065027043700	0.01643152506679130	19.450409919002100
20230525190	12.00796482051090	0.02488734692835970	19.322899966289100
20230525195	11.922910747104000	0.02956453063978280	18.76783861852790
20230526152	11.773632748076900	0.01339230316726210	18.81269806646480
20230526154	11.722830070057400	0.0415484793856597	18.88964808449430
20230527144	11.882869206933600	0.01620124216848660	18.456930256969600
20230527150	11.849920390627400	0.03901564600961690	18.928456537020800
20230528153	11.78450743468340	0.01926683008159470	18.446731915116800

4.2 Light Curve Results

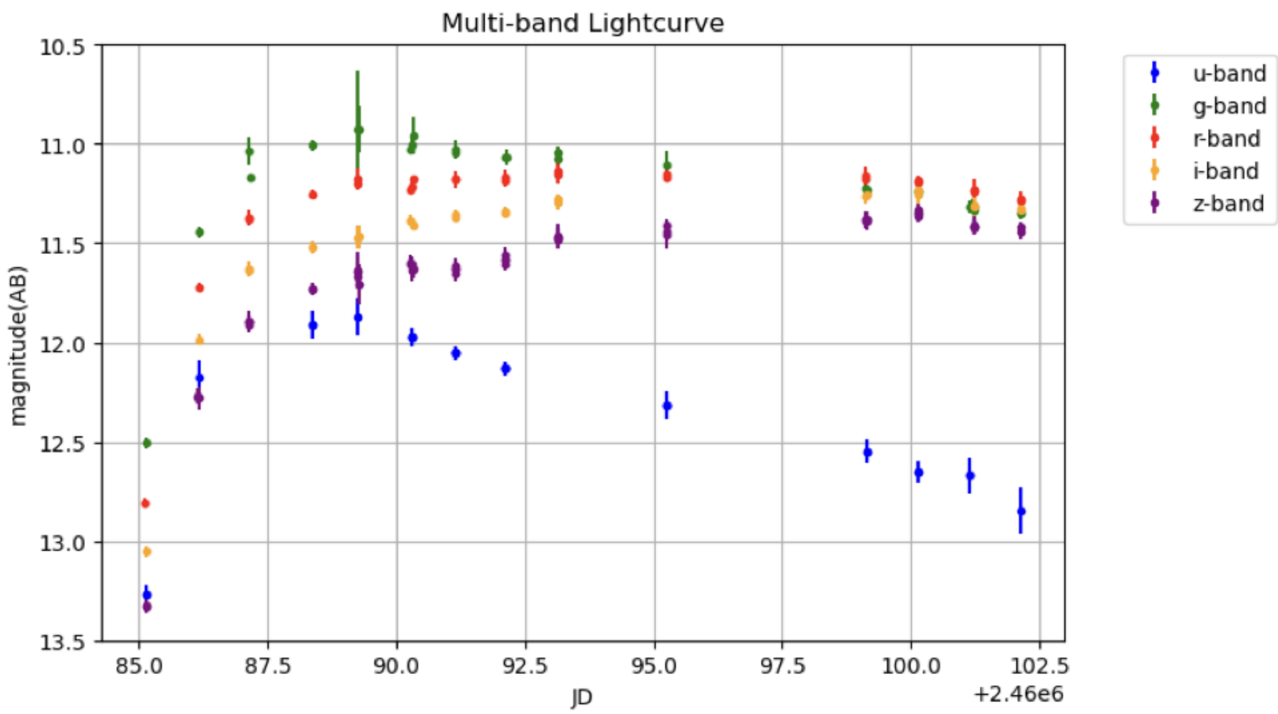


Figure 4.2: Obtained LightCurve from Data

r-band Data

Date	Magnitude	e_magnitude	lim_mag
20230520150	14.15155422821890	0.24937038948549600	19.43685781735160
20230521151	13.573298439343800	0.13500155881386600	18.596849554896000
20230521155	12.804603974199400	0.23680389471793300	20.102492545364000
20230522151	12.6353700072121	0.25473024872802500	19.945871345538600
20230522153	12.524061271917300	0.2465370422671170	19.830622668703300
20230523211	12.513461694561500	0.25543989469431600	19.816996523794000
20230524175	12.086183263609800	0.25864007967321400	18.916719070522800
20230524175	12.393973118048500	0.2889069580594830	19.292213269936600
20230525183	12.391112976702000	0.2754302946472250	19.8821967403049
20230525190	12.48135849334210	0.27418106019860300	19.796314900832300
20230526152	12.23556403322570	0.2880003980451320	19.60330201079100
20230526153	12.182339778968200	0.2944495684405660	19.391888197023700
20230527144	12.29990928286550	0.2698030183307950	19.31058333165310
20230527145	12.29261384433820	0.2813972753818810	19.165053094227500
20230528151	12.425793901413700	0.21797534577101100	18.976172985357100
20230528151	12.436979177202800	0.22086221215440100	18.704868678182200
20230530175	12.248420824347700	0.2624497913740790	18.697560285170100
20230530180	12.474061639553200	0.25765953258585400	19.05722502302300
20230603145	12.522757768008300	0.2881490746779240	19.17320607746860
20230603150	12.530620538938000	0.2524740572756290	18.907571643039800
20230604150	12.508330430444800	0.24634259374135900	19.37097191278930
20230604151	12.355725203890400	0.2835851458817450	19.249743463885600
20230605172	12.264211976684600	0.18594445885282200	18.84955229386920
20230605173	12.293737505546200	0.25862179889822000	18.99443187680150
20230606145	12.427533104228500	0.2976298679486130	19.525736158908700
20230606150	12.333918027833600	0.30026448602568300	19.415619240498700

I-band Data			
Date	**Magnitude**	**e_magnitude**	**lim_mag**
20230520152	14.496698333042900	0.5145913736875790	19.566506784422900
20230521155	13.171632816699400	0.5086915709058490	19.7297439238054
20230522153	12.920437258363800	0.5032841924985950	19.865406617827000
20230522153	12.905048122310500	0.5037154320145820	19.897230862635200
20230523205	12.965961300340500	0.5007378961111290	19.57887934918740
20230524180	13.075398944893200	0.5226701608845710	18.774319310065800
20230524182	13.035060215908600	0.5474635493392590	18.79595148943940
20230525183	12.715811512129300	0.5274626743400910	19.854854881491500
20230525184	12.770189552495100	0.5110497732086490	19.690937206243900
20230525195	12.842890536014400	0.5138422690688760	19.210377647548700
20230526152	12.616595342921600	0.5424724403014340	19.820349070894800
20230526154	12.612741455828700	0.5378195836486370	19.823664161611300
20230527145	12.72369272323890	0.5579829802456880	19.51420464573040
20230527150	12.704135882299100	0.5142044101298150	19.583912558693800
20230528151	12.77784375453300	0.40676845621424200	18.78664953782230
20230528152	12.691039811933900	0.5792136012402940	18.969625221333800
20230530180	12.419209741590900	0.5926600084820850	16.883570189678100
20230603150	12.848350675888900	0.560723808616758	19.27734689353390
20230603151	12.793981158515400	0.5384326271588450	19.382132778023500

u-band Data		
JD	**Magnitude**	**e_magnitude**
2460085.134521930	13.27090536014810	0.04734162156478220
2460085.134521930	13.27090536014810	0.04734162156478220
2460086.15681593	12.16306539238130	0.08151348552875540
2460088.377300140	11.911942995258100	0.06909705934451160
2460088.377300140	11.911942995258100	0.06909705934451160
2460089.2596239000	11.875623852176900	0.09076130776088580
2460089.2596239000	11.875623852176900	0.09076130776088580
2460090.2917486900	11.972426554352100	0.04833800711317820
2460090.2917486900	11.972426554352100	0.04833800711317820
2460090.2917486900	11.972426554352100	0.04833800711317820
2460090.2917486900	11.972426554352100	0.04833800711317820
2460091.15255333	12.054344061072100	0.03358433105525660
2460091.15255333	12.054344061072100	0.03358433105525660
2460091.15255333	12.054344061072100	0.03358433105525660
2460091.15255333	12.054344061072100	0.03358433105525660
2460092.1279825900	12.129977319509700	0.034668366590219300
2460092.1279825900	12.129977319509700	0.034668366590219300
2460092.1279825900	12.129977319509700	0.034668366590219300
2460092.1279825900	12.129977319509700	0.034668366590219300
2460095.2447050600	12.319263557355700	0.07253907241650530
2460095.2447050600	12.319263557355700	0.07253907241650530
2460095.2447050600	12.319263557355700	0.07253907241650530
2460095.2447050600	12.319263557355700	0.07253907241650530
2460099.1386030800	12.548687064949400	0.05830964472348440
2460099.1386030800	12.548687064949400	0.05830964472348440
2460100.14777306	12.64817455134130	0.05488934499306140

5. Modelling

We model the light curve of the SN2023ixf using the **Superbol** package. We found the Energy , temperature and radius variation of SN2023ixf using data from the various bands.The flux was then blackbody corrected.

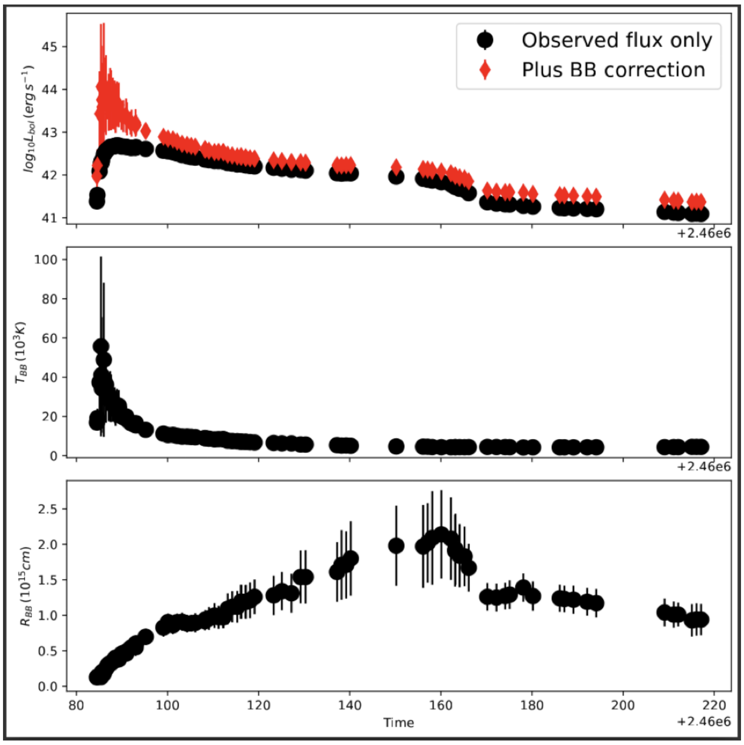


Figure 5.1: SN2023ixf Properties

Next we found the luminosity of SN2023ixf using the blackbody corrected spectrum and using the formula

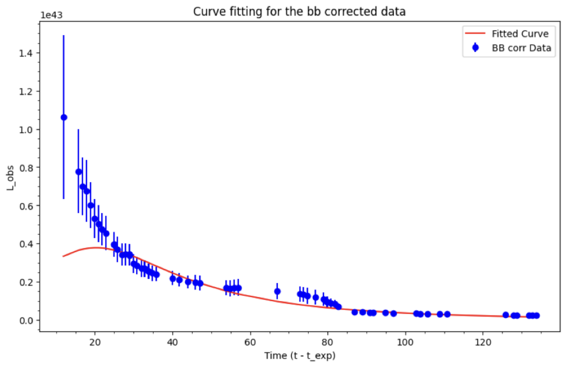


Figure 5.2: Fitted Luminosity

By fitting the luminosity of the we can extract the Mass of Nikel(Ni) formed in the ejecta and also about the progenitor of the SN2023ixf by constraining Nikel mass using various stellar model.
We use the following formula for fitting

$$L(t) = L_0.M_{Ni}\left(\exp\frac{-\Delta t}{t_{Co}} - \exp\frac{-\Delta t}{t_{Ni}}\right)\left(1 - \exp\left(\frac{t_c}{\Delta t}\right)^2\right)$$

where,

- M_{Ni} = Mass of Nikel-56
- t = Time elapsed after explosion
- t_c = Charcterstics time of diffusion
- t_{Co} = Decay time of Cobalt
- t_{Ni} = Decay time of Nikel

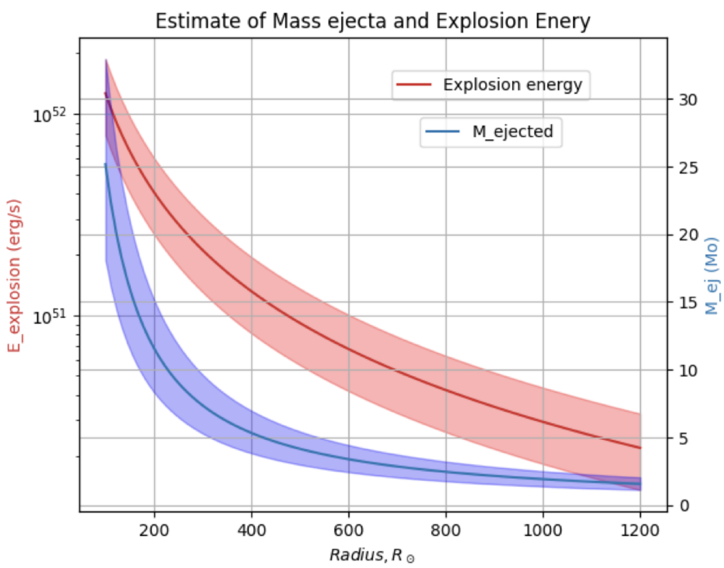


Figure 5.3: Mass and Energy of Explosion

Energy and Nikel Mass produced in the SN2023ixf was estimated using the following formulas:

$$log_{10}(E_{51}) = -0.728 + 2.148 log_{10}(L_{42}) - 0.280 log_{10}(M_{Ni}) + 2.091 log_{10}(t_{p2}) - 1.632 log_{10}(R_{500})$$

(3)

$$log_{10}(M_{10}) = -0.947 + 1.474 log_{10}(L_{42}) - 0.518 log_{10}(M_{Ni}) + 3.967 log_{10}(t_{p2}) - 1.120 log_{10}(R_{500})$$

where,

- M_{10} = Ejecta Mass in units of 10 solar mass
- R_{500} = Progenitor Radius in units of 500 solar radius
- t_{p2} = Plateau phase duration in units of 100 days
- L_{42} =Luminosity 50 days after explosion in units of 10^{42} erg/s
- M_{Ni} = Mass of Nikel produced

We found that,

Mass of Nikel

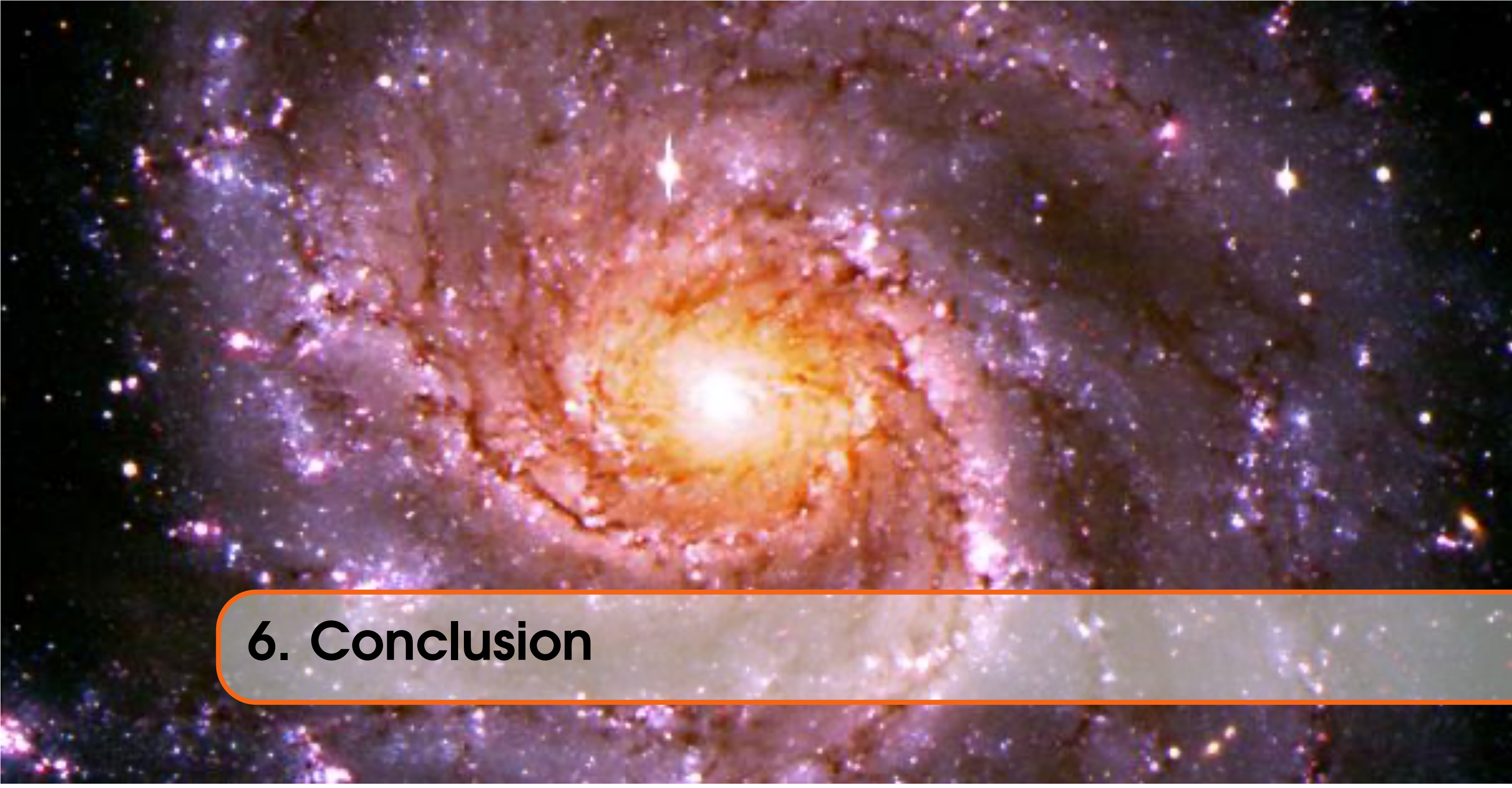
$$\boxed{M_{Ni} = 0.04 M_{\odot}}$$

Energy of explosion,

$$\boxed{E = 3 \times 10^{51} erg/s}$$

Radius of Progenitor

$$\boxed{R = 200 - 300 R_{\odot}}$$



6. Conclusion

In this project I have used the raw data of the SN2023-ixf and then used image reduction techniques to make the data useful for science based applications. Furthermore, I learnt to techniques such as Astrometry and Photometry and used them first to convert image coordinates to sky-coordinates and then extract magnitudes of supernova using Photometric Techniques. I extracted magnitude of supernova over various days in u,g,i,r bands. In this project I have used Softwares like psfex and sextractor and techniques like aperture photometry and psf-photometry to get the light curve of SN2023ixf.
In this process the u-band data needs an additional techniques due to very less no. of stars to estimate the lightcurves and we need to reject those stars that shows high variations in brightness over days. In the last part of the project I modelled the light curve to extract the physical properties of the supernovae such as ejecta mass, explosion energy and progenitor radius etc.
I also studied about why SN2023ixf was an importrant probe for the CSM(CircumStellar Medium) as shocks from supernova and how it interacted with the CSM gave us a great oppurtunity to probe it .Also its unusual short peak time combined with its proximity to us provided us a valuable chance to study about properties of the SN-TypeII properties.

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