ASTR 4750 Computational Astrophysics

Project 1: Supernova Light Curve Modeling

Nageeb Zaman and Trang Huynh

09/15/2022

Abstract

Using Arnett's analytical model we wrote a code to produced the Luminosity of type Ib/c Supernova as a function of time (light curve). We fitted the radioactive decay tail of the light curve with an exponential function. We plotted the light curve for different values of the Ni-56 mass and different ejecta mass, and we also plotted the low progenitor radius light curve. Lastly we produced a plot of peak luminosity verses time to reach peak luminosity for these different light curves we got in previous steps and analyzed the plots.

1 Introduction

A supernova is a transient astronomical event that happens when a star (usually 8-12 times mass of sun) during the last evolutionary stages exhausts its nuclear fuel in the core and explodes with extreme brightness. The original star, the progenitor, either collapses to a neutron star or black hole, or is completely destroyed. Supernovae are classified using their light curves and the absorption lines of different chemical elements. For this project we only study the Type Ib/c supernovae. Type Ib/c supernovae which results from a star with extended hydrogen envelope reaches the peak luminosity with 1-2 weeks and then the luminosity declines within similar timescales. Then it reaches a constant decline rate which is governed by the amount of radioactive ^{56}**Ni** and ^{56}Co produced during the explosion. Using Arnett's law we can model the light curve which is the plot of luminosity of the supernovae against time, if we already know the mass of the radioactive ^{56}**Ni**, mass of the ejecta, diffusion time scale of the ejecta, and the velocity of the ejecta. We created a python code which plots the light curve of the supernova using the parameters mentioned above. We also fitted decay tail of the light curve with an exponential function then we changed the input parameters to get different light curves to see how the input parameters affect the light curves.

2 Arnett's Supernova Light curve model

Arnett's supernova Light curve model has the following form:

$$L(t) = \frac{2M_{Ni}}{t_d} e^{-\left[\frac{t^2}{t_d^2} + \frac{2R_o t}{v t_d^2}\right]} [(\epsilon_{Ni} - \epsilon_{Co}) \int_0^t \left[\frac{R_o}{v t_d} + \frac{t'}{t_d}\right] e^{\left[\frac{t'^2}{t_d^2} + \frac{2R_o t'}{v t_d^2}\right]} e^{-\frac{t^2}{t_{Ni}}} + \epsilon_{Co} \int_0^t \left[\frac{R_o}{v t_d} + \frac{t'}{t_d}\right] e^{\left[\frac{t'^2}{t_d^2} + \frac{2R_o t'}{v t_d^2}\right]} e^{-\frac{t^2}{t_{Co}}}$$

Here L is the luminosity in ergs/s units, t is time in days, M_{Ni} is the total mass of the radioactive ^{56}**Ni** produced, t_d is the diffusion time-scale for radiation to escape in days, R_o is the radius of the progenitor, v is the ejecta velocity, t_{Ni} and t_{Co} are the characteristic half life time scales of Ni and Co, ϵ_{Ni} and ϵ_{Co} are the specific energies due to the radioactive decay of these elements.

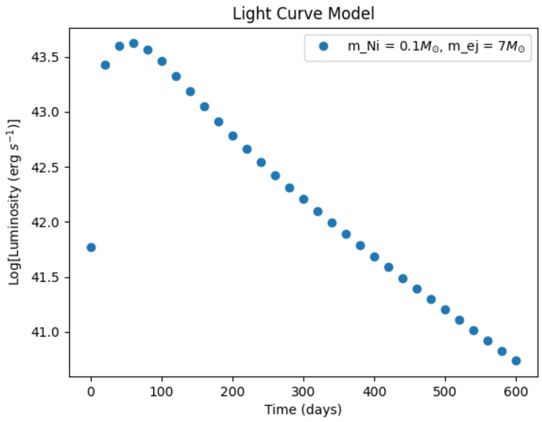

Figure 1: Luminosity vs. time Graph for v = 7000km/s, R_o = 10^{13}cm,M_{ej} = $7M_\odot$, and M_{Ni} = 0.1 $M_\odot$

3 Results and Analysis

3.1 Part 1

The first part in modeling the light curve is to calculate the integrals in Arnett's formula. We did this using the Simpsons method in the Scipy.integrate package. We created a method in our code that takes in input of an time array and the necessary parameters like M_{Ni},M_{ej},R_o and v and returns the luminosity corresponding to the time array. So, the method calculates the luminosity for each time in the time array and returns the luminosity for each time in an array.

3.2 Part 2

In Fig.1 We plotted the luminosity verses the time graphs using the matplotlib package.

3.3 Part 3

After we have the light curve we now fitted the decaying exponential tail of the light curve with an exponential equation Ae^{-Bt}. To do that we first needed to separate the light curves tail. We used a function np.max() to get the

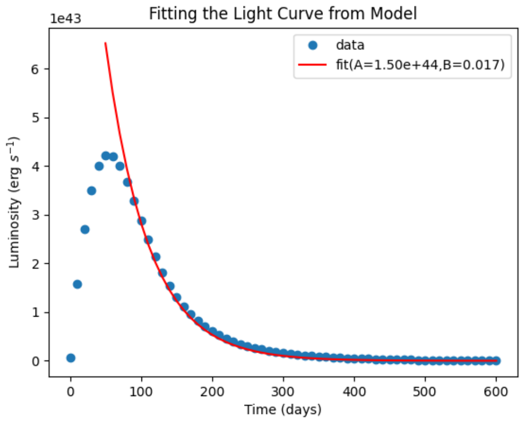

Figure 2: Luminosity vs. time with curve fitting for v = 7000km/s, R_o = 10^{13}cm,M_{ej} = 7$M_{\odot}$, and M_{Ni} = 0.1 $M_{\odot}$

maximum luminosity from the luminosity array and then we stored the luminosity after the maximum into a separate array. Then using curve fit method from scipy.optimize package and a pre-defined exponential function we fitted the tail of the light curve. Then we plotted the luminosity with the curve fit in Fig.2.

The fitting parameters are $A = 1.5 * 10^{44}$ and $B = 0.017$. Unfortunately we could not find any constants that would fit these values of the coefficients.

3.4 Part 4

For the next study we plotted the light curve for different values of the parameters. First we plotted the LC for a low and a high value of M_{Ni}. We chose $0.01M_{\odot}$ and $0.5M_{\odot}$. Then we plotted the LC for a low and a high value of M_{ej}. We chose $1M_{\odot}$ and $20M_{\odot}$. We included all the curves in a single plot. The plot is shown in Fig.3.

We can see that the luminosity peak increases with higher M_{Ni} and peak luminosity decreases with higher M_{ej}. So, if we have more Ni the supernova will be more luminous. And if we have more ejecta the luminosity is going to decrease.

3.5 Part 5

In this study we re-computed the original model with only R_o changed to zero. So we are setting the progenitor radius to zero. We plotted the light curve for this in Fig.4.

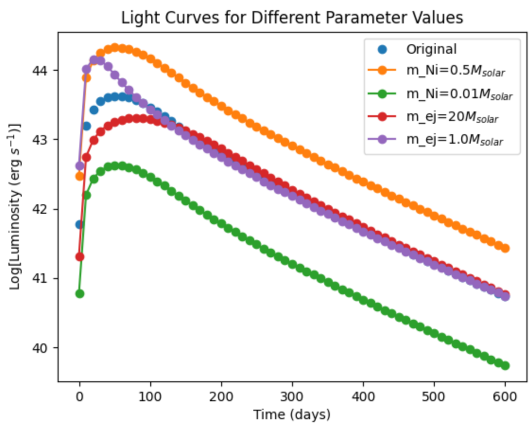

Figure 3: Luminosity vs. time with different M_{Ni} and M_{ej}

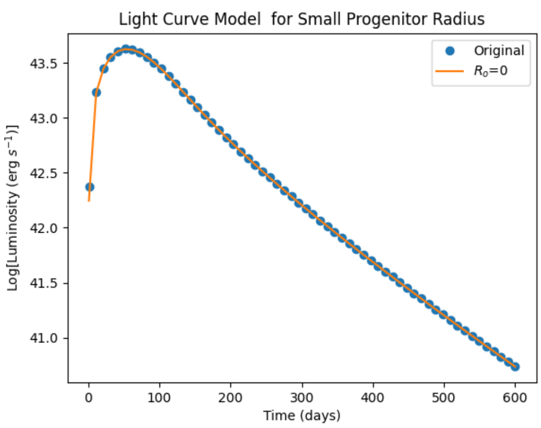

Figure 4: Luminosity vs. time with $R_o = 0$

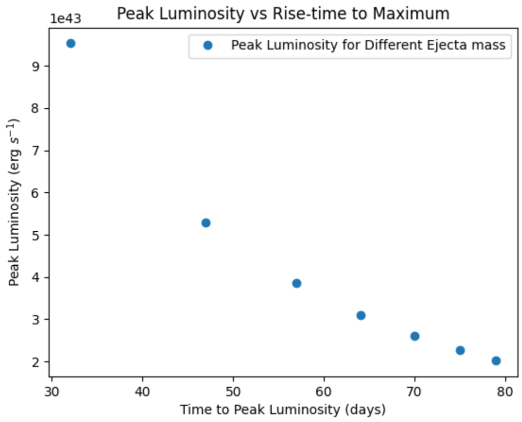

Figure 5: Peak Luminosity vs. rise-time to maximum for different M_{ej}

we can see form the figure that the light curve has no effect if the progenitor radius is set to zero. Which makes sense in the approximation that a star is an ideal blackbody.

3.6 Part 6

In this study we plot the light curve for varying ejecta mass so that we can see how the luminosity and the rise-time to maximum varies with different ejecta mass. We calculated the maximum luminosity and the time corresponding to the maximum luminosity for different ejecta mass. The figure 5 shows the plot of peak luminosity verses rise-time to maximum.

We can see that as M_{ej} increases peak luminosity decreases and time to rise increases. If we have more ejecta then the supernova is less luminous and it takes more time reach peak luminosity.

4 Conclusions

For this project we used different python packages and methods to model the light curve of a supernova. We created many plots of the light curve with varying parameters and analyze them. This gave us a idea about how we can create model for light curves that we can use to fit an observed light curve of a supernova and study the various parameters, which will give us insights into the nature of the supernova.