MNRAS 000, 1–3 (2024) Preprint 31 October 2024 Compiled using MNRAS LATEX style file v3.3

Simulating stellar populations in the Milky Way using Montecarlo

Catalina Riveros-Jara[1]★
[1] *Universidad Técnica Federico Santa María*

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

In this study, we use Montecarlo simulations to model the stellar population of the Milky Way, focusing on the distribution of main sequence stars and stellar remnants. Using the Kroupa's Initial Mass Function (IMF) to create random samples, we simulated five star samples of different sizes (number of objects) to simulate the galaxy's stellar mass and stellar remnant distributions. The simulations classified stars into main sequence stars, white dwarfs, neutron stars, and black holes based on their initial masses and calculated their final masses and ages. Results indicate that approximately 70% of stars in each sample remain on the main sequence, while the most common remnants are white dwarfs, which what was expected according to the IMF's prediction of a higher prevalence of low-mass stars. Additionally, we observe that increasing sample sizes led to distributions that more closely predicted expected real populations. This approach illustrates the effectiveness of Montecarlo methods in stellar population synthesis and provides insights into the current remnant populations of our galaxy.

Key words: stars: abundances – stars: evolution – stars: low-mass – stars: black holes – (stars:) white dwarfs

1 INTRODUCTION

Understanding the stellar populations of galaxies has been a central topic of research in astrophysics, as stars play a fundamental role in shaping galactic structure and evolution. Stars are born and evolve through various stages, actively fusing different elements in their cores, until they reach the end of their lives turning into stellar remnants. The study of stellar evolution and populations is then essential to comprehend the mechanisms of galaxy evolution.

Our galaxy, the Milky Way, hosts billions of stars that evolve along different paths primarily determined by their initial mass. To date, three main types of stellar remnants have been identified: white dwarfs, neutron stars, and black holes. The Initial Mass Function (IMF), as proposed by Kroupa (2001), suggests that the majority of stars in our galaxy are low-mass stars, destined to end their lives as white dwarfs—cold, exposed cores no longer capable of fusion, as described by Cataln et al. (2008).

Various techniques allow us to sample the stellar population of the Milky Way and to determine the initial-to-final mass relation of its stars. In this work, we aim to simulate the fraction of each type of stellar remnant in our galaxy, analyzing their mass and age distributions using a Montecarlo simulation. This computational technique uses random sampling to approximate complex mathematical functions and physical systems. By generating five distinct samples of stars and applying Kroupa's IMF, we assess whether these simulated techniques reliably represent the observed stellar population in the Milky Way.

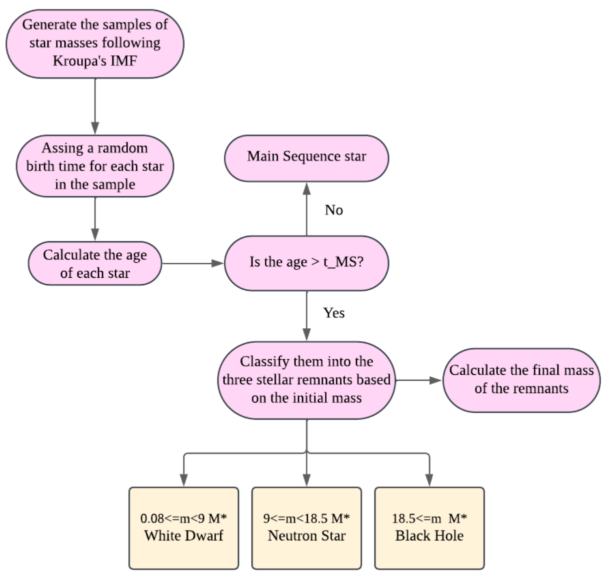

Figure 1. Flowchart describing the main steps followed in this work.

2 METHODS

Figure 1 summarizes each step followed to calculate the fraction and final mass of each star in the samples. All steps are going to be specified in the following sections.

★ E-mail: catalina.riverosj@usm.cl

2.1 Montecarlo Simulation

In this work, we use a Montecarlo simulation to model the stellar population of the Milky Way, specifically aiming to estimate the distribution of stellar remnants: white dwarfs, neutron stars, and black holes. A Monte Carlo simulation is a computational technique that uses repeated random sampling to model complex systems and estimate their statistical properties. This method is particularly effective for modeling systems with significant uncertainty or complex interactions, as it allows for the generation of numerous potential outcomes based on probabilistic inputs.

We randomly generate five large samples of initial stellar masses based on the Initial Mass Function (IMF) defined by Kroupa (2001).

2.2 Sample of stars

We started by creating five different random samples of stars in *Python*, following Kroupa's IMF, with masses between $0.08\mathrm{M}_\odot$ and $100\mathrm{M}_\odot$. Each sample contained 100, 1000, 10000, 100000 and 1000000 stars respectively in the same range of masses.

2.3 Initial Mass Function (IMF)

In order to describe how its the initial distribution of masses of the stars on each of the samples, we used the *Initial Mass Function* proposed by Kroupa (2001), that follows the next set of equations:

$$\xi(m) \propto m^{-\alpha_i} \tag{1}$$

$$\begin{aligned}
\alpha_0 &= +0.3 \pm 0.7 & 0.01 \le m/M_\odot < 0.08 \\
\alpha_1 &= +1.3 \pm 0.5 & 0.08 \le m/M_\odot < 0.50 \\
\alpha_2 &= +2.3 \pm 0.3 & 0.05 \le m/M_\odot < 1.00 \\
\alpha_2 &= +2.3 \pm 0.7 & 1.00 \le m/M_\odot
\end{aligned} \tag{2}$$

Where m is the initial mass of the star.

2.4 Ages of the stars

We assigned a random time of birth between 0 and 10 [Gyr], the age we assumed for the Milky Way, for each sample mentioned in Section 2.2 following a uniform distribution. We then calculated the approximated main sequence lifetime of each star following showed by Carroll & Ostlie (2006):

$$T_{MS} = \frac{10^{10}}{M^{2.5}}[years] \tag{3}$$

Where M is the mass of the star. Then, the current age or lookback time of each star is given by:

$$Age = 10 - \frac{T_{MS}}{10^9}[Gyr] \tag{4}$$

Eq. (3) and (4) were used to find how many stars of each sample are still in the main sequence and how many of them are now stellar remnants. Assuming the red giant evolution phase is too short along the evolution of the star, then the condition to classify each star as a main sequence star or a stellar remnant is the following:
We classified them as stellar remnants if:

$$Age > T_{MS} \tag{5}$$

Analogously, the stars are still in the main sequence if:

$$Age < T_{MS} \tag{6}$$

2.5 Remnant mass and classification

Based on the initial mass of each star, we classified them into three stellar remnants: white dwarfs, neutron stars or Black Hole, based on the following mass ranges:

$$\begin{aligned}
0.08M_\odot \le m < 9M_\odot &\ ;\ \text{White Dwarf} \\
9M_\odot \le m < 18.5M_\odot &\ ;\ \text{Neutron Star} \\
18.5M_\odot \le m &\ ;\ \text{Black Hole}
\end{aligned} \tag{7}$$

According to Kalirai et al. (2008) the final mass of a star that is ending its life as a White Dwarf is given by eq.(8)

$$M_{\text{final}} = (0.109 \pm 0.007)M_{\text{initial}}0.394 \pm 0.025M_\odot \tag{8}$$

For neutron stars, there are different equations that dictate the final mass of the remnant based on the initial mass of the star, in this work we followed the proposed set of equations by Raithel et al. (2018):
$9 \le M_{\text{initial}} \le 13M_\odot$:

$$\begin{aligned}
M_{\text{final}} &= 2.24 + 0.508(M_{\text{initial}} - 14.75) \\
&+0.125(M_{\text{initial}} - 14.75)^2 + 0.011(M_{\text{initial}})
\end{aligned} \tag{9}$$

$13 \le M_{\text{initial}} < 15$:

$$M_{\text{final}} = 0.123 + 0.112M_{\text{initial}} \tag{10}$$

$15 \le M_{\text{initial}} < 17.8$

$$M_{\text{final}} = 0.996 + 0.0384M_{\text{initial}} \tag{11}$$

$17.8 \le M_{\text{initial}} < 18.5$

$$M_{\text{final}} = -0.020 + 0.10M_{\text{initial}} \tag{12}$$

For black holes, we also followed the set of equations proposed by Raithel et al. (2018) (assuming an ejection fraction $f_{EJ} = 0.9$):
$18.5 \le M_{\text{initial}} < 40$:

$$\begin{aligned}
M_{\text{BH-core}} &= -2.049 + (0.4140M_{\text{initial}}) \\
M_{\text{BH-all}} &= 15.52 - 0.3294 \cdot (M_{\text{initial}} - 25.97)^2 \\
-0.02121 \cdot (M_{\text{initial}} &- 25.97)^2 + 0.003120 \cdot (M_{\text{initial}} - 25.97)^3 \\
M_{\text{final}} &= 0.9 \cdot M_{\text{BH-core}} + (1 - 0.9) \cdot M_{\text{BH-all}}
\end{aligned} \tag{13}$$

$40 \le M_{\text{initial}}$:

$$M_{\text{final}} = 5.697 + 7.8598 \cdot 10^8 \cdot M_{\text{initial}}^{(-4.858)} \tag{14}$$

3 RESULTS

Figure 2 shows the distribution of the stellar masses following Kroupa's IMF for the five samples. It can be seen that all samples show the same behavior, predicting more low-mass stars. Moreover, when increasing the number of stars, the decay in the IMF for high-mass stars is more evident, which is what was expected.

On the other hand, when adding a random birth time for the stars, the more stars we sample, the more likely they are to be homogeneously distributed throughout the entire age of the Milky Way, meaning that throughout the lifetime of our galaxy, almost the same amount of stars are born on each time range, that is shown in Figure 4.

Following the condition given by eq.(3) and the initial mass conditions given by eq.(8), (9), (10), (11), (11), (13) and (14), we obtained the fraction of each remnant of each sample, which can be seen in Figure 4 and the amount of each class is summarized in Table 1.

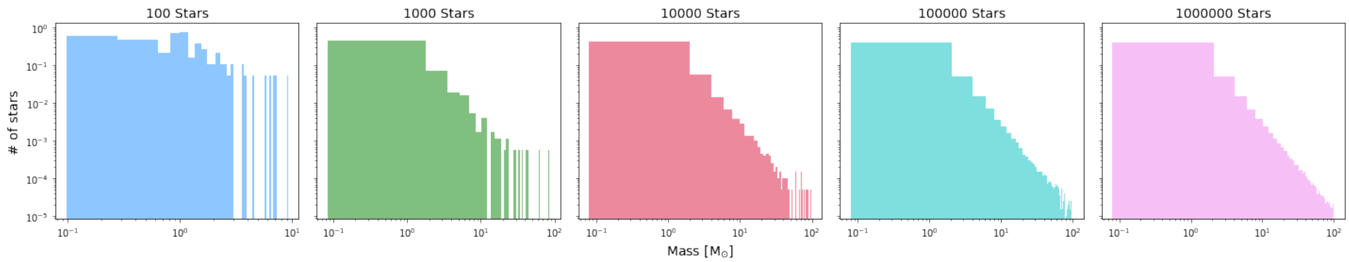

Figure 2. Mass distribution based on Kroupa's IMF for each of the five samples.

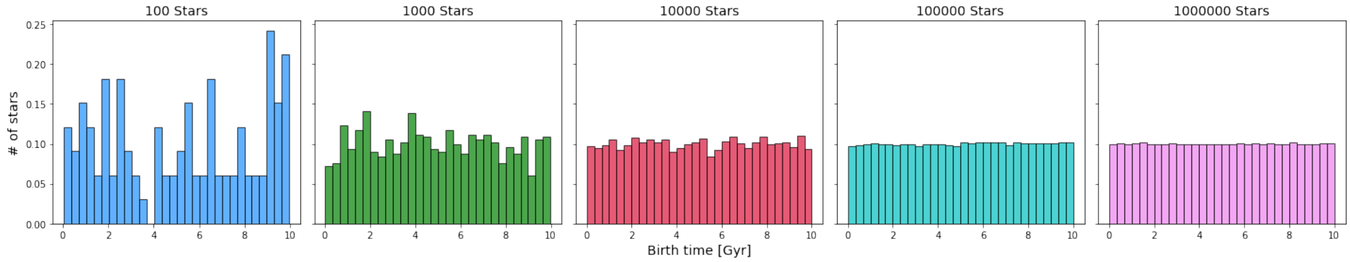

Figure 3. Time of birth for the five samples. This time was randomly selected from a uniform distribution.

Table 1. Fraction of the stars in the Main Sequence (MS) and of each type of remnant: White Dwarfs (WD), Neutron Stars (NS) and Black Holes (BH), for the five samples.

Sample	MS	WD	NS	BH
100 stars	0.740	0.260	0	0
1000 stars	0.729	0.242	0.019	0.010
10000 stars	0.708	0.269	0.015	0.008
100000 stars	0.703	0.272	0.016	0.009
1000000 stars	0.701	0.274	0.016	0.009

Based on the same set of equations, the distribution of the final masses for each class is shown in Figure 5 and the age distribution can be seen in Figure 6.

When adding more stars to the sample, it can be observed that, with increasing mass, the number of the stars in the main sequence decreases while the more massive remnants are black holes. The amount of white dwarf and neutron stars are distributed in a narrower range of masses meaning that these remnants are less massive and their masses are concentrated in a certain range, being the more numerous ones, the white dwarfs. For the ages, when increasing the amount of stars, we can see that the number of white dwarfs increase with time while the other classes remain in an almost similar amount throughout the age of the Milky Way.

4 CONCLUSIONS

The Montecarlo simulations carried in this study effectively approximated the current distribution of main sequence stars and stellar remnants within the Milky Way. By applying Kroupa's IMF, we generated five different star samples, providing a statistical model of our galaxy's stellar mass distribution. As expected, increasing the sample size led to simulations that more accurately reproduced the observed distributions of stellar masses, which is the main porpuse of using Montecarlo simulations.

Our results show that approximately 70% of the simulated stars remain on the main sequence in all samples, which is in accordance with predictions from stellar evolution theory. White dwarfs are the most abundant remnant type, confirming the expected outcome based on the IMF, which predicts a higher fraction of low-mass stars that evolve into white dwarfs. The mass distribution of neutron stars and black holes, although less frequent, is in agreement with theoretical expectations for higher-mass stars. This work reflects how useful a Montecarlo simulation be in trying to reproduce stellar populations in the Milky Way.

Future research could improve the model by including metallicity variations and different star formation histories, which would allow for a more comprehensive and realistic understanding of the factors shaping the galactic stellar population over time.

REFERENCES

Carroll B. W., Ostlie D. A., 2006, An Introduction to Modern Astrophysics, 2nd edn. Addison-Wesley, San Francisco

Cataln S., Isern J., Garca-Berro E., Ribas I., 2008, Monthly Notices of the Royal Astronomical Society, 387, 1693–1706

Kalirai J. S., Hansen B. M. S., Kelson D. D., Reitzel D. B., Rich R. M., Richer H. B., 2008, The Astrophysical Journal, 676, 594–609

Kroupa P., 2001, Monthly Notices of the Royal Astronomical Society, 322, 231–246

Raithel C. A., Sukhbold T., Özel F., 2018, The Astrophysical Journal, 856, 35

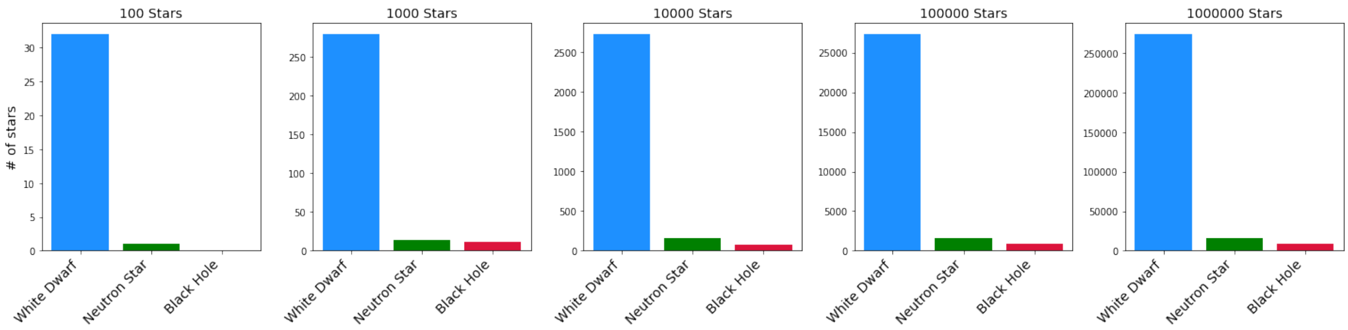

Figure 4. Number of stellar remnants of each sample. The blue bar corresponds to the amount of white dwarfs on each sample, the green bar to the amount of neutron stars and the red bar to the amount of black holes.

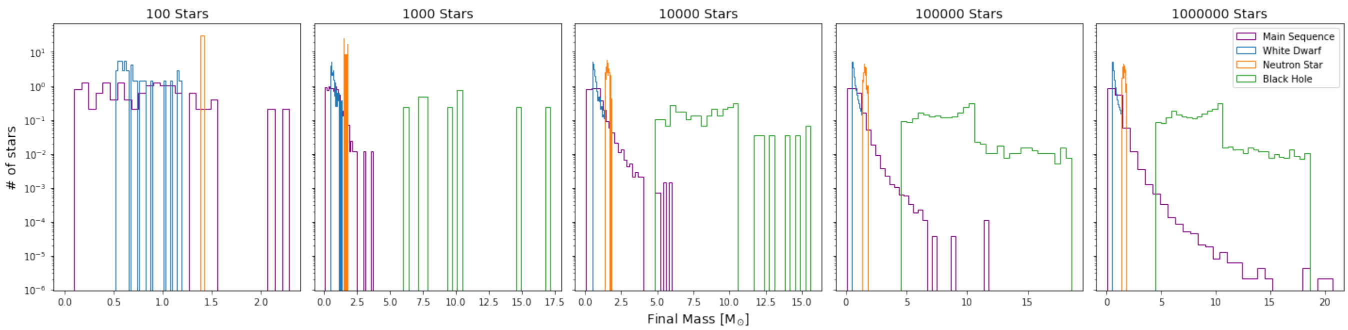

Figure 5. Final mass distributions of the stars that remain in the main sequence and the three types of remnants. The purple line corresponds to the Main Sequence stars, the blue line corresponds to the fraction of white dwarfs, the orange line corresponds to the neutron stars and the green lines to the black holes.

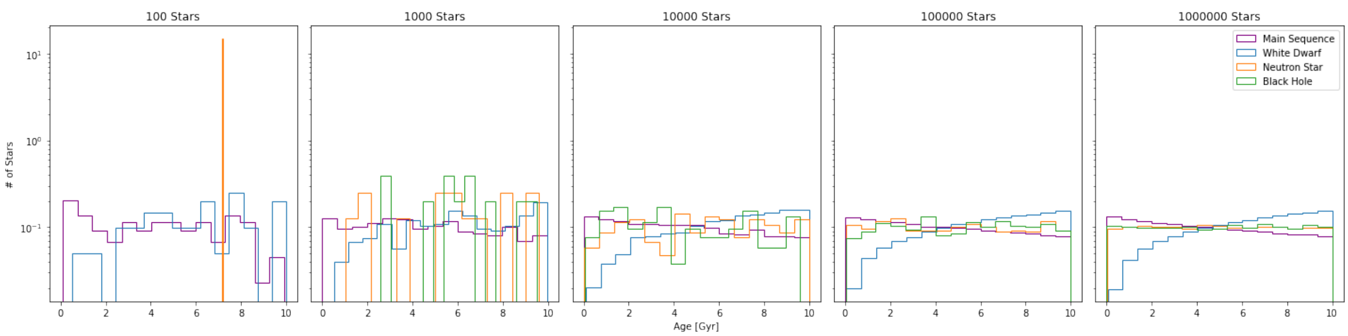

Figure 6. Final age distributions of the stars that remain in the main sequence and the three types of remnants. The purple line corresponds to the Main Sequence stars, the blue line corresponds to the fraction of white dwarfs, the orange line corresponds to the neutron stars and the green lines to the black holes.