Evolution of the ingredients of the Milky Way

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ABSTRACT
This paper presents an evolutionary stellar population model that employs Monte Carlo simulations, an initial mass function, and initial-to-final mass relations to trace the life cycles of stars within the Milky Way. The primary objective of this study is to investigate the distribution of stars in this galaxy and interpret the findings. The results indicate a higher likelihood of low-mass stars in the population, with 93% of stars remaining on the main sequence, 6.4% evolving into white dwarfs, 0.4% becoming neutron stars, and 0.2% transforming into black holes. These outcomes align with existing literature, validating the effectiveness of the code for fundamental analysis. The next step would involve developing a more advanced code with additional features for more in-depth analysis. The code and documentation are available on GitHub (https://github.com/javieravivanco/Stellar-Model-Javiera-Vivanco.)

Key words: Stellar Population Model – Milky Way – White dwarfs – Neutron stars – Black holes

1 INTRODUCTION

The Milky Way has long captivated the attention of astronomers and astrophysicists due to its stellar population and its complex evolution, composed of the main-sequence stars that populate its spiral arms and the stellar remnants such as white dwarfs, neutron stars, and black holes.

The stars in the main sequence represent a central phase in stellar life, where nuclear fusion of hydrogen into helium provides the necessary energy for their characteristic brightness. Most stars spend the majority of their lives in this stage before progressing to the next evolutionary phase. On the other hand, stellar remnants are objects that have already passed through the main sequence stage, reaching their final phase. White dwarfs are the remnants of low to intermediate-mass stars that have exhausted their nuclear fuel and expelled their outer layers. Neutron stars and black holes, result from supernova explosions in massive stars, and in the case of black holes, they undergo an intense gravitational collapse.

To understand this stellar population, it is essential to utilize evolutionary stellar population synthesis models. Given the vast number of stars in the galaxy, it becomes impractical to simulate each individual star. Instead, it is more practical to create a theoretical population that mimics the real one.

In this study, the aim is to construct a model by merging the Monte Carlo method with the initial mass function formulated by Kroupa (2001) to generate a population and its mass distribution. Subsequently, by attributing them a birth age, taking into account the star formation rate, and calculating their main sequence lifetimes, initial-to-final mass relations for each of the three stellar types, as described by Kalirai et al. (2008) and Raithel et al. (2018), can be incorporated to determine their ultimate fate. This model will be utilized to simulate the evolution of the stellar population within the Milky Way.

2 METHODS

2.1 Evolutionary stellar population model

The code developed for simulating the evolution of a stellar population performs the following tasks: It generates a population of stars within the Milky Way, each with a specified age at birth. It calculates the main sequence lifetime for each star. It distinguishes the stars that transition into stellar remnants, classifies the specific type of remnant they evolve into, and calculates their final mass. These properties will be elaborated upon in the subsequent subsections.

2.1.1 Initial mass and birth time

The process starts with the generation of a specified number of stars, each assigned random initial masses. To achieve this, a combination of the Monte Carlo method and Kroupa (2001)'s initial mass function is employed. Kroupa (2001)'s function (Eq. 1) is a multi-segmented power-law distribution that defines the probability of stars existing within specific mass ranges. The values of α_i in the IMF reflect how the distribution of initial masses of stars varies for that ranges. The function employed in the code is defined in a manner that ensures its continuity across the entire mass range, using constants for each segment. This function is shown on Figure 1. Consequently, if the generated probabilities align with the distribution proposed by Kroupa (2001), the star is considered as a part of the created population.

$$\xi\left(m\right) = m^{-\alpha_i} \tag{1}$$

To assign a birth time to the stars, it is assumed that the star formation rate (SFR) remains constant over time for the sake of simplicity. Consequently, star births are randomly drawn from this rate. Then, knowing the age of the Milky Way, ~10 [Gyr], makes it straightforward to calculate the total age of the stars.

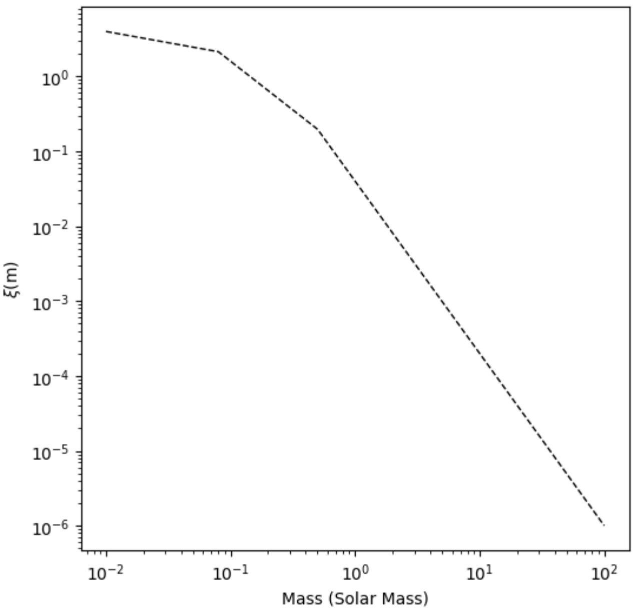

Figure 1. Initial mass function by Kroupa (2001), ξ (m) v/s m, explained in 2.1.1.

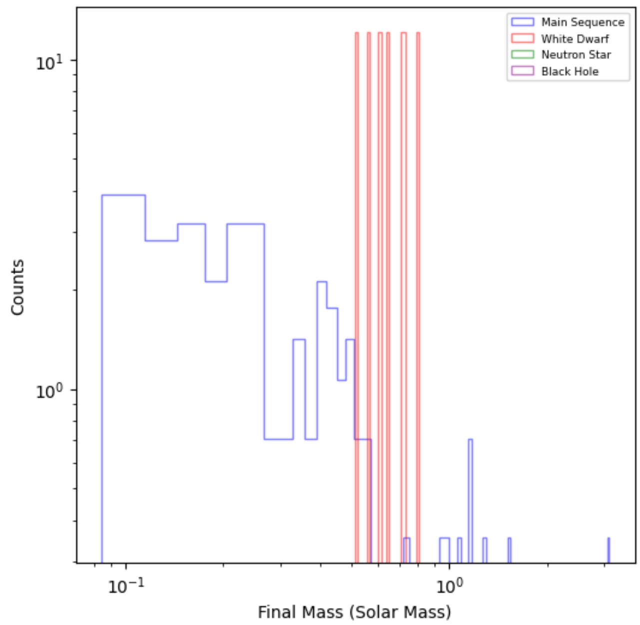

Figure 2. Normalized histogram of final masses for a simulation of 100 stars. This sample excludes black holes (BH) and neutron stars (NS), making it a bad representation of the Milky Way.

2.1.2 *Main Sequence lifetime and Stellar remnants*

The next step is the calculation of the main sequence (MS) lifetime for each star, a task accomplished using Eq. 2 (derived from the mass-luminosity relation) due to the availability of mass data. Then, a comparison is made between the total age of the stars and their respective MS lifetimes, leading to the classification of stars into those that remain on the MS and stellar remnants.

$$T_{MS} = 10^{10}/M^{2.5} \tag{2}$$

Finally, the code categorizes the stellar remnants into white dwarfs (WD), neutron stars (NS), and black holes (BH) and determines their final masses. This is done using three initial to final mass relations (IFMR), one for each remnent. The WD IFMR comes from Kalirai et al. (2008), derived empercially, and the NS and BH IFMRs are described by Raithel et al. (2018).

While the WD IFMR is straightforward, as it uniformly applies within a restricted mass range, the IFMRs for NSs and BHs are more complex. They exhibit variations across different mass branches for each type of remnant. Additionally, there are overlapping mass intervals where the formation of both NSs and BHs is plausible. To address this, each initial mass within these overlapping ranges is assigned a random probability of becoming either an NS (> 0.5) or a BH (< 0.5), thus facilitating the application of the respective IFMR.

2.2 Simulation

The model described in subsection 2.1 is intended for simulating the evolution of a Milky Way population. The galaxy comprises billions of stars; however, that it's a very large number even for a basic simulation, due to its vast scale. Therefore, samples of various sizes were simulated, including 100, 1000, 10000, 100000, and 1000000 stars. It was observed that the results from the smaller samples lack descriptiveness due to limited data. For instance, as depicted in Figure 2, running a simulation with 100 stars shows an absence of NS and BH, which is inconsistent with the well-established fact that they exist in the galaxy. Consequently, the study will be carried out using a sample of 1 million stars, with mass values ranging from 0.08 to 100 solar masses ($M_\odot$).

3 RESULTS

Through the application of the simulation model, a stellar population of one million stars was generated, as depicted in Figure 3, the IMF plot illustrates the distribution of masses. Notably, lower-mass stars exhibit a high probability (approaching 1) of existence, resulting in a greater number of them being formed. Conversely, higher-mass stars possess a considerably lower probability, leading to their more limited presence in the population.

Continuing with the simulation code, it results in a population comprising 929,949 stars on the Main Sequence (93%), 64,007 white dwarfs (6.4%), 4,076 neutron stars (0.4%), and 2,242 black holes (0.2%). Black holes (BH) have a lower occurrence because they require high initial masses, and, as previously explained, the formation of objects with higher masses is less likely. This is consistent with what is presented in the literature: There are between 10^8-10^9 neutron stars in the Milky Way (Sartore, N. et al. (2010)), which corresponds to approximately 0.1-1% of the total stellar population, and the fraction obtained falls within this range. The Milky Way is estimated to contain around 1.2×10^8 single black holes (Olejak et al. (2020)), which accounts for approximately 0.12% of the total stellar bodies, that is in relatively close agreement with the mentioned results. In addition, white dwarfs make up 95% of stellar remnants (Breivik et al. (2020)), which aligns with the results obtained (91%).

The final masses of these stars are depicted in the normalized histogram shown in Figure 4. Notably, WDs exhibit the lowest masses among the three types of remnants, while BHs are the most massive. NSs have higher masses than WDs but lower than BHs. In fact, it is

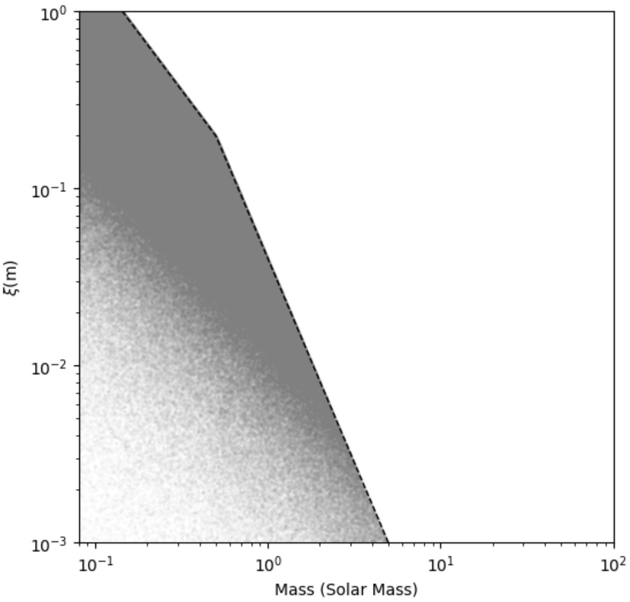

Figure 3. Initial mass function by Kroupa (2001), alongside the initial masses generated as gray data points.

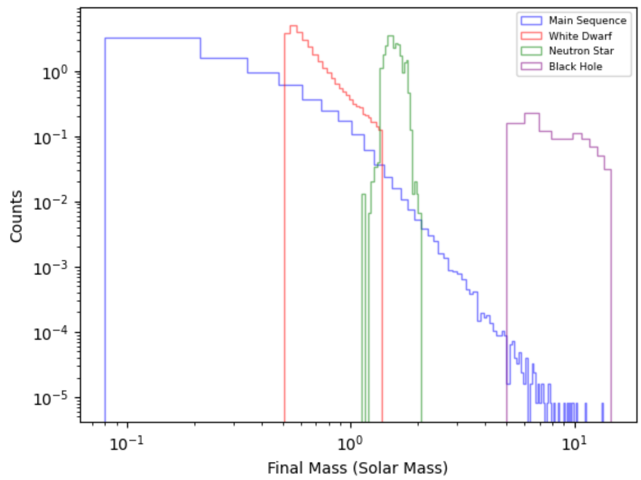

Figure 4. Normalized histogram of final masses for a simulation of 1,000,000 stars, differentiated by stellar body.

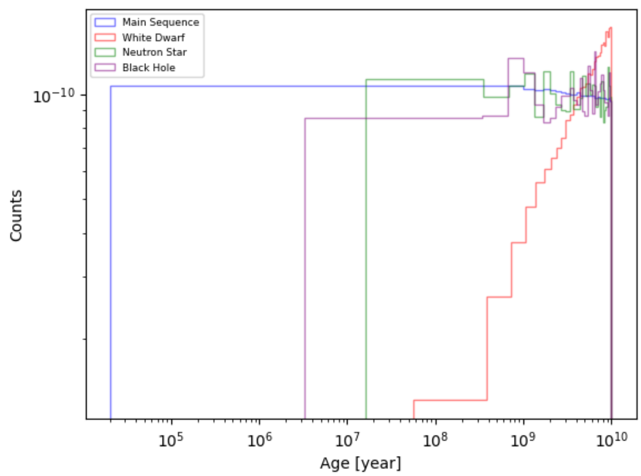

Figure 5. Normalized histogram of stellar ages for a simulation of 1,000,000 stars, differentiated by stellar body.

worth mentioning that some NSs have final masses similar to those of WDs. The final mass of a neutron star depends largely on the amount of material expelled during the supernova explosion and how much mass is retained in the core. Thus, in this case, the expulsion of material during the supernova could be efficient enough to allow the resulting neutron star to have a mass similar to that of a white dwarf. Furthermore, it's worth noting that stars on the MS possess notably low masses, a characteristic attributed to the distribution of initial masses.

Another approach for comparing these objects is through a normalized histogram of the ages of each stellar body, as shown in Figure 5. It is evident that the stellar remnants are older than many stars on the MS, as they have exceeded their MS lifetimes and, consequently, have existed for a longer period. Notably, all white dwarfs are characterized by their advanced age, whereas neutron stars and black holes exhibit a broader range of ages, with BHs displaying the widest age distribution among the three types of remnants. WDs are generally very old, as their formation is related to the stellar evolution of stars like the Sun, which will eventually consume their nuclear fuel and go through a series of stages before becoming white dwarfs. NSs and BHs, on the other hand, are the outcome of supernova explosions in massive stars at the end of their lives, which can occur at different stages of a massive star's life, resulting in remnant stars with varied ages.

4 CONCLUSIONS

The model used for simulating the Milky Way offers a convenient way to understand the distribution of stellar objects in terms of mass and type. After conducting a simulation with 1 million stars, the results show that Milky Way's population consists of 93% of stars on the main sequence, 6.4% white dwarfs, 0.4% neutron stars, and 0.2% black holes, which aligns with findings from previous research. It's worth noting that stellar remnants are the oldest objects in this population, as they have surpassed the main sequence phase. Among them, white dwarfs have the earliest lower age limit, while neutron stars and black holes can form at various points in a star's evolution.

To enhance the code's accuracy, one potential improvement could involve considering a theoretical Star Formation Rate (SFR) - Time relation instead of assuming a constant SFR. This would result in more precise assignments of the birth ages of stars. In the future, additional features could be incorporated to capture the evolving characteristics of stars, such as their radius, luminosity, element fractions on the interior, and more. However, this marks a promising starting point for the modeling of evolutionary stellar populations.

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