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THE INFLUENCE OF METALLICITY ON HELIUM AND CO CORE MASSES IN MASSIVE STARS

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SUMMARY: We present the results of 58 detailed evolutionary models of massive single stars and close binary systems with the Solar and Small Magellanic Cloud (SMC) metallicity computed with the MESA (Modules for Experiments in Stellar Astrophysics) numerical code. Helium core masses of single stars (30 $M_{\odot}$ - 75 $M_{\odot}$) with metallicities of 0.02 and 0.0021 are in the range of 9.26 $M_{\odot}$ - 29.56 $M_{\odot}$ and 11.62 $M_{\odot}$ - 33.96 $M_{\odot}$, respectively. Their carbon-oxygen (CO) core masses are between 5.44 $M_{\odot}$ and 25.04 $M_{\odot}$ vs. 8.23 $M_{\odot}$ and 28.38 $M_{\odot}$ for the Solar vs. SMC metallicity, accounting for an average difference of 25%. To investigate the influence of metallicity on helium and carbon-oxygen core masses in massive close Case A binary systems, detailed evolutionary models of binary systems in the mass range of 30 $M_{\odot}$ to 40 $M_{\odot}$ are calculated. The initial orbital period is set to 3 days and the accretion efficiency to 10%. The helium core mass range for primary stars with lower metallicity is 10.61 - 16.21 $M_{\odot}$ vs. 7.94 - 11.69 $M_{\odot}$ for $z = 0.02$. The resulting CO core masses of primary stars for the SMC metallicity are on average about 50% larger than for the Solar metallicity, so the effect is more prominent than in the case of single stars. The black hole formation limit for primary stars with the SMC metallicity is under 30 $M_{\odot}$. While the least massive primary stars with Solar metallicity end up as neutron stars, all primary stars with the SMC metallicity and all secondary stars complete their evolution as black holes. The double compact objects resulting from the presented models are of two types: mixed neutron star-black hole systems (4 models) and double black holes (18 models). We also derive the relation between the final helium core mass and the carbon-oxygen core mass and show that it does not depend on metallicity. We confirm the CO/helium core mass ratio to be larger in binary systems than for single stars.

Key words. Binaries: close – Stars: massive – Stars: evolution – Stars: black holes – Stars: neutron

1. INTRODUCTION

Massive stars are unique Nature´s laboratories. They undergo all nuclear-burning stages up to a formation of an iron-nickel core and end their lives with supernovae or quiet collapses into black holes (Heger et al. 2000, Heger and Langer 2000, Langer 2012). The metallicity, i.e. the amount of elements heavier than helium, has a significant influence on the evolution of massive stars, most importantly by affecting the line-driven stellar winds and, in this way, also the mass of their final stellar remnants.

The dependence of stellar wind mass loss on metallicity has been established by many authors in preceding decades (Lucy and Solomon 1970, Pauldrach et al. 1986, Kudritzki and Puls 2000, Vink and Sander 2021) and it was shown that changing the mass-loss rates of massive stars by only a factor of two has a dramatic effect on their evolution (Meynet et al. 1994). These differences in stellar wind mass loss rate result in a more or less prominent stellar mass decline during the main sequence evolution and helium core burning phase with a consequence of different (initial and final) helium and carbon-oxygen core masses.

In massive binaries, the stellar mass of both components decreases only due to the stellar wind mass loss before possible interaction i.e. mass transfer takes place (Petrovic et al. 2005, Wellstein and Langer 1999) and this stellar wind mass loss rate influences the mass of each star in its Wolf-Rayet phase, as well as the mass of their helium cores and, in this way, also the mass of their final stellar remnants - neutron stars or black holes.

The influence of metallicity on the massive star evolution became even more important by the Virgo/LIGO discovery of the gravitational waves (GW) (Abbott et al. 2016a,b,c, 2019, 2021) linked with mergers in double compact object systems, remnants of massive binary systems. To determine progenitor evolution of such gravitational wave GW sources, it is necessary to consider the impact of metallicity on the resulting helium and carbon-oxygen (CO) core masses, and in this way, the compact object masses.

In this paper we investigate the influence of metallicity on the final helium and CO core masses for single and binary stars. We present evolutionary models of single stars in the range of 30 $M_\odot$ - 75 $M_\odot$ and models of massive binary systems with initial masses in the range between 30 $M_\odot$ and 40 $M_\odot$, with the selected mass ratio of 0.9, accretion efficiency of 10% and the initial period of 3 days.

All presented evolutionary models of non-rotating massive single and binary stars were calculated with the MESA (Modules for Experiments in Stellar Astrophysics) code (Paxton et al. 2011, 2013, 2015, 2018) in revision 10398. Both single and binary models were calculated for the Solar (z = 0.02) and the Small Magellanic Cloud (SMC) metallicity (z = 0.0021). The other details about input parameters are given in Petrovic (2021) and Petrović (2022).

The paper is structured as follows: the details of evolutionary models of single stars are given in Section 2 and binary systems in Section 3. The Discussion and Conclusions are given in Section 4.

2. SINGLE-STAR MODELS

Models of single stars with metallicity 0.02 and 0.0021 have been calculated for masses between 30 $M_\odot$ and 75 $M_\odot$: with the step of 1 $M_\odot$ between 30 $M_\odot$ and 40 $M_\odot$ and step of 5 $M_\odot$ above 40 $M_\odot$. The evolution of single stars has been calculated through the main sequence and core helium burning phase until the formation of their CO cores. Helium and CO core masses of single-star models are listed in Table 1.

Fig. 1 shows masses of helium and CO cores for single-star models for both metallicities. It can be noticed that the resulting cores for the SMC metallicity are visibly more massive. This is expected as a result of lower stellar wind mass loss during their evolution (see for example Vink and Sander (2021)). Helium core masses for metallicity of 0.02 and 0.0021 are in the range of 9.26 - 29.56 $M_\odot$ and 11.62 - 33.96 $M_\odot$, respectively. At the same time CO core masses for the Solar metallicity are between 5.44 and 25.04 $M_\odot$ vs. 8.23 and 28.38 $M_\odot$ for the SMC metallicity. While helium and CO core masses for the Solar metallicity closely follow a linear correlation, there is much more scatter for $z = 0.0021$ models.

The mass of the resulting He and CO cores for z = 0.02 can be fitted with the following linear approximations:

$$M_{\rm He} = 0.44869 M_{\rm in} - 3.93107, \quad (1)$$

$$M_{\rm CO} = 0.42194 M_{\rm in} - 6.38068. \quad (2)$$

For the metallicity of 0.0021, the approximations are given with:

$$M_{\rm He} = 0.51521 M_{\rm in} - 3.56262, \quad (3)$$

$$M_{\rm CO} = 0.46752 M_{\rm in} - 5.51518. \quad (4)$$

where $M_{\rm in}$ is the initial stellar mass, $M_{\rm He}$ is the mass of the final helium core and $M_{\rm CO}$ the mass of the CO core.

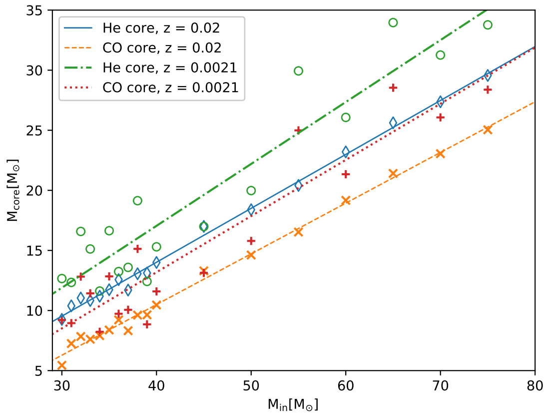

Fig. 1: Helium and carbon-oxygen core masses as a function of the initial stellar masses for single stars with the Solar (diamonds - He core, x - CO core) and Small Magellanic Cloud metallicity (circles - He core and + - CO core). The lines represent linear approximations for the He and CO core masses for both metallicities.

It can be concluded that there is a general influence of the metallicity on helium and CO core masses. The values of CO core masses are on average about 25% larger for the SMC metallicity compared to the Solar. Since BH masses can be estimated from the CO core masses (Belczynski et al. 2010), this indicates that stars born in less metal-rich environments will produce more massive remnants. However, it should be kept in mind that the values of the SMC metallicity resulting from our calculated models are largely scattered and the magnitude of CO core mass increase varies significantly for different initial stellar masses.

Table 1: Evolutionary models of single stars with $z = 0.02$ and $z = 0.0021$. $M_{\rm in}$ - initial stellar mass, $M_{\rm He}$, $M_{\rm CO}$ - the final helium core and CO core mass.

$M_{\rm in}$	$M_{\rm He}(0.02)$	$M_{\rm CO}(0.02)$	$M_{\rm He}(0.0021)$	$M_{\rm CO}(0.0021)$
30.0	9.26	5.44	12.66	9.21
31.0	10.39	7.25	12.34	8.95
32.0	11.04	7.84	16.58	12.82
33.0	10.83	7.61	15.12	11.43
34.0	11.19	7.91	11.62	8.23
35.0	11.73	8.38	16.64	12.84
36.0	12.57	9.22	13.24	9.73
37.0	11.70	8.32	13.59	10.06
38.0	13.06	9.62	19.14	15.13
39.0	13.12	9.64	12.42	8.85
40.0	14.00	10.46	15.30	11.59
45.0	17.00	13.30	16.99	13.13
50.0	18.39	14.62	19.98	15.79
55.0	20.41	16.53	29.94	24.99
60.0	23.20	19.17	26.07	21.34
65.0	25.62	21.41	33.96	28.54
70.0	27.37	23.05	31.26	26.07
75.0	29.56	25.04	33.77	28.38

3. BINARY SYSTEM MODELS

The calculated models follow binary evolution from two massive main sequence O-type stars, through the Case A and Case AB mass transfer to the formation of a CO core in primary stars. Further evolution of secondary stars is modeled in a single star approximation to the formation of CO core, also with the MESA numerical code.

The initial mass ratio and accretion efficiency were selected as described in Petrović (2022): to avoid evolution into contact, the mass ratio is selected to be near 1 (Wellstein et al. 2001) and accretion efficiency is set to 10% as this was indicated by previous WR+O binary models (Petrovic et al. 2005).

To investigate the influence of metallicity (Langer 2012, Vink and Sander 2021) on the evolution and helium and carbon-oxygen core masses in Case A binary systems, we have calculated 11 evolutionary models of binary systems with the Solar ($z = 0.02$) and 11 models with the Small Magellanic Cloud metallicity ($z = 0.0021$). The initial masses are in the range of 30 $M_\odot$ to 40 $M_\odot$ and an initial orbital period is set to 3 days. The helium and CO core masses are given in Table 2.

Considering the comparison between binary systems with two different metallicities, Table 2 shows that the masses of resulting He and CO cores are systematically larger for the SMC metallicity. The CO core masses in primary stars for the SMC metallicity are on average about 50% larger than the Solar metallicity, so the influence is more prominent than for single stars. On the other hand, there is no systematic influence on the CO core masses of secondary stars, as those are much more influenced by the large amounts of material accreted during Case A and Case AB mass transfer.

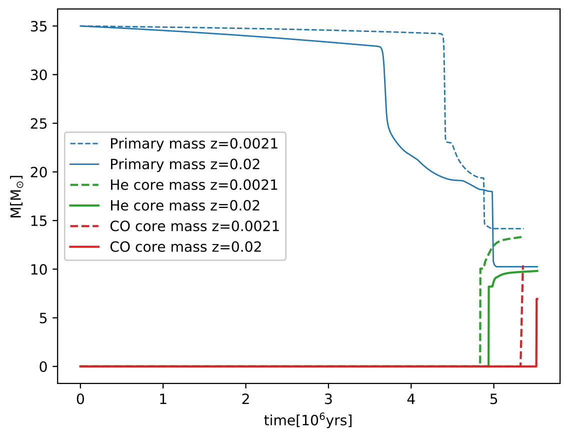

Fig. 2: Mass of a primary star in binary system 35 $M_\odot$ + 31.5 $M_\odot$ with an initial orbital period of 3 days for both values of metallicity, as well as helium and CO core masses for both systems.

As an example, Fig. 2 shows the mass of a primary star in binary system 35 $M_\odot$ + 31.5 $M_\odot$ with an initial orbital period of 3 days for both values of metallicity, as well as helium and CO core masses for both systems. In this plot, Case A mass transfer is shown as the first sudden drop in stellar mass and Case AB as the second. Before mass transfer starts, primary stars lose mass only due to the stellar winds. It is clearly visible that the stellar wind mass loss prior to Case A is lower for metallicity of 0.0021, as expected. As a results, the final primary mass for the lower metallicity is 14.17 $M_\odot$ vs 10.25 $M_\odot$ for z = 0.02. Because of this, the masses of helium and carbon-oxygen cores are also larger for lower metallicity. The helium core for the SMC metallicity is about 13.36 $M_\odot$, roughly 3.5 $M_\odot$ larger than for z = 0.02. The CO core mass for lower z is 10.30 $M_\odot$ vs 6.95 $M_\odot$ for $z = 0.02$.

While for the Solar metallicity, the CO core masses of primary stars in binary systems are in average 15% lower than the ones of single stars with the same initial masses (Petrović 2022), the CO cores for the SMC metallicity (Table 1 and 2) in binary primaries are not always less massive than their single star counterparts.

The final vs. the initial helium core masses are shown for both metallicities in Fig. 3. Due to the lower stellar wind mass loss, the final values for helium core masses are larger for lower metalilcity, as expected. It can be observed that the values for z = 0.02 follow the linear correlation very clearly, while the values for z = 0.0021 have more scatter, but still can be fitted with the following expression:

$$M_{\rm He,f} = 1.15428 M_{\rm He,in} + 1.81771. \tag{5}$$

Fig. 4 shows masses of helium and CO core of primary stars for all calculated binary systems as a function of the initial primary mass, for both metallicities, as well as the linear fits for single stars, also for both z. It can be seen that, in calculated binary systems, the resulting core masses for z = 0.0021 are systematically larger than for z = 0.02. The resulting helium cores in binary systems have masses in range 10.61 $M_\odot$ - 16.21 $M_\odot$ (z = 0.0021) and 7.94 $M_\odot$ - 11.69 $M_\odot$ (z = 0.02). At the same time, the CO core masses are between 7.76 $M_\odot$ and 12.95 $M_\odot$ and between 5.26 $M_\odot$ and 8.85 $M_\odot$ for the SMC and Solar metallicity, respectively.

The linear approximations for resulting helium and CO core masses in the presented models with metallicity of 0.0021, mass ratio of 0.9, and primary masses in the range of 30 $M_\odot$ - 40 $M_\odot$ are:

$$M_{\rm He} = 0.64227 M_{\rm in} - 8.83318, \tag{6}$$

$$M_{\rm CO} = 0.57373 M_{\rm in} - 9.57045. \tag{7}$$

The corresponding approximations for the binary systems with Solar metallicity have been derived in Petrović (2022).

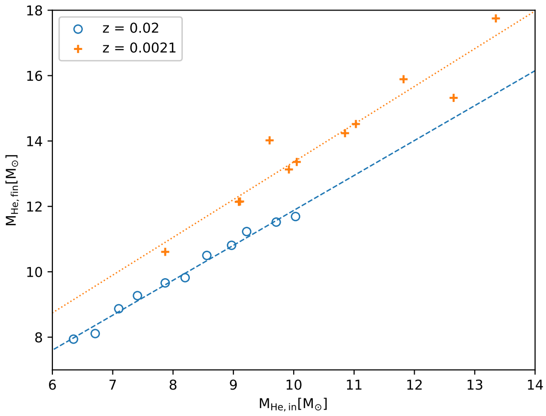

Fig. 3: The mass of the initial and final He core for binary systems with the initial orbital period of 3 days for metallicity $z = 0.02$ and $z = 0.0021$.

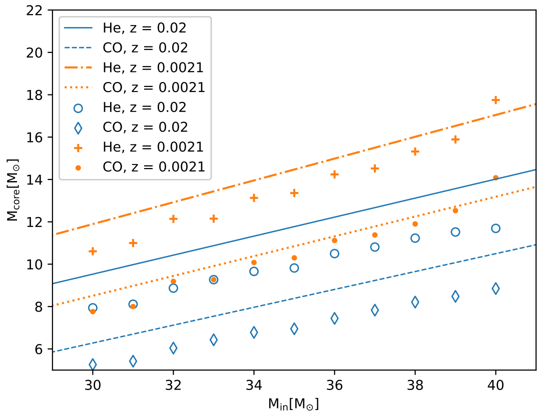

Fig. 4: The mass of the He and CO core for binary systems with the initial orbital period of 3 days for metallicity z = 0.02 and z = 0.0021 as a function of initial mass. The lines represent linear fits for single stars for both metallicities.

4. DISCUSSION AND CONCLUSION

Single-star models presented in this paper show the difference of about 25% in CO core mass between the Solar and the SMC metallicity models in mass range 30 $M_\odot$ - 75 $M_\odot$. As expected, the lower metallicity induces lower stellar wind mass loss and, because of this, a less significant decrease of stellar mass during the evolution.

The influence of binarity on CO core masses in primary stars appears to be more complex and dependent on the metallicity, as well as on the initial binary orbit.

Previously, Petrović (2022) showed that the Solar metallicity primary stars with masses in the range 30 $M_\odot$ - 40 $M_\odot$ evolving in binary systems with initial

Table 2: Evolutionary models with $z = 0.0021$ and $z = 0.02$ for initial orbital period of 3 days and accretion efficiency of 10%. $M_{1,\mathrm{in}}, M_{2,\mathrm{in}}$ - initial primary and secondary mass, $M_{\mathrm{WR}} + M_{\mathrm{O}}$ - mass of the primary and secondary in Wolf-Rayet (WR) + O phase, $p_{\mathrm{WR,O}}$ - orbital period in WR + O phase, $M_{\mathrm{PSN}} + M_{\mathrm{MS}}$ - mass of the primary and the secondary before the first supernova explosion, p_{PSN}- the orbital period before the first supernova explosion, $M_{1,\mathrm{He}}/M_{1,\mathrm{CO}}$ - final helium core and CO core mass for the primary star, $M_{2,\mathrm{He}}, M_{2,\mathrm{CO}}$ - final helium and CO core mass for the secondary star. The CO core boundary is the outermost location where the helium mass fraction falls below 0.01.

$M_{1,\mathrm{in}}$	$M_{2,\mathrm{in}}$	$M_{\mathrm{WR}} + M_{\mathrm{O}}$	$p_{\mathrm{WR,O}}$	$M_{\mathrm{PSN}} + M_{\mathrm{MS}}$	p_{PSN}	$M_{1,\mathrm{He}}$	$M_{1,\mathrm{CO}}$	$M_{2,\mathrm{He}}$	$M_{2,\mathrm{CO}}$
z=0.0021									
30.0	27.0	13.83 + 28.17	9.64	11.25 + 28.26	14.74	10.61	7.76	13.08	9.65
31.0	27.9	16.22 + 29.30	7.42	15.36 + 28.80	8.26	14.02	10.75	13.28	9.79
32.0	28.8	13.26 + 30.08	12.14	12.79 + 30.06	12.42	12.14	9.19	14.05	10.56
33.0	29.7	14.97 + 30.89	9.96	12.85 + 30.88	13.25	12.15	9.27	14.92	11.30
34.0	30.6	16.53 + 31.65	8.61	13.90 + 31.69	12.11	13.13	10.08	15.21	11.56
35.0	31.5	16.14 + 32.64	9.62	14.17 + 32.63	12.24	13.36	10.30	15.81	12.12
36.0	32.4	18.84 + 33.60	7.39	15.19 + 33.27	10.90	14.24	11.12	15.86	12.14
37.0	33.3	16.86 + 34.44	9.85	15.42 + 34.41	11.31	14.52	11.38	17.37	13.56
38.0	34.2	20.00 + 34.72	7.18	17.02 + 35.09	9.97	15.32	11.90	17.46	13.60
39.0	35.1	20.05 + 36.03	7.68	17.10 + 36.02	10.14	15.89	12.53	17.06	13.20
40.0	36.0	23.75 + 36.68	5.87	19.90 + 36.37	7.98	16.21	12.95	19.26	15.25
z=0.02									
30.0	27.0	12.59 + 27.07	10.65	8.26 + 27.20	27.24	7.94	5.26	12.30	8.96
31.0	27.9	13.02 + 27.84	11.00	8.43 + 27.81	28.18	8.10	5.42	13.72	10.33
32.0	28.8	13.53 + 28.63	10.98	9.21 + 29.00	26.78	8.84	6.06	13.99	10.57
33.0	29.7	13.84 + 29.53	11.64	9.65 + 29.93	27.00	9.25	6.43	14.90	11.40
34.0	30.6	14.76 + 30.13	10.98	10.06 + 30.49	26.23	9.65	6.78	15.85	12.29
35.0	31.5	15.41 + 30.86	10.64	10.25 + 30.99	25.84	9.82	6.95	14.88	11.40
36.0	32.4	15.88 + 31.58	10.58	10.88 + 32.02	25.00	10.48	7.44	16.87	13.21
37.0	33.3	16.45 + 32.28	10.41	11.27 + 32.64	24.20	10.80	7.83	16.79	13.03
38.0	34.2	16.08 + 33.07	11.51	11.70 + 33.51	23.80	11.22	8.21	18.48	14.64
39.0	35.1	17.64 + 33.75	10.00	12.00 + 34.01	23.12	11.52	8.48	17.24	13.56
40.0	36.0	18.21 + 34.84	9.80	12.21 + 35.19	23.41	11.69	8.85	16.97	13.37

orbital periods of 3, 4, and 5 days have on average about 15%, 8% and 2.5% smaller CO cores than single stars with same initial masses.

Results presented in this paper show that there is no such systematic decrease in CO core masses due to binarity for the models with the SMC metallicity presented in this paper. On the contrary, in models with $z = 0.0021$, CO cores of primary stars evolving in binary systems are sometimes even more massive than their single-star CO core counterparts.

Considering the influence of metallicity on CO core masses in binary systems, our calculated models show that the CO cores of primaries with $z = 0.02$ are systematically about 50% less massive than for $z = 0.0021$. This implies that for reproducing some of the most massive double BHs indicated by Virgo and LIGO, models with lower metallicity should be considered.

According to Tauris et al. (2015), if a CO core mass is above 6.5 $M_{\odot}$, then a black hole is formed. Below this limit (and above 1.435 $M_{\odot}$), supernova explosion will leave a neutron star as a relic. In our models, primary stars are stripped of their hydrogen envelopes almost entirely. The masses of hydrogen envelope that is left after two mass transfers (Case A and Case AB) and stellar wind mass loss are in the range of 0.3 - 0.4 $M_{\odot}$ for $z = 0.02$ and about 1 $M_{\odot}$ for $z = 0.0021$. We assumed the same for secondary stars, since those are most likely to be stripped in a common envelope evolution.

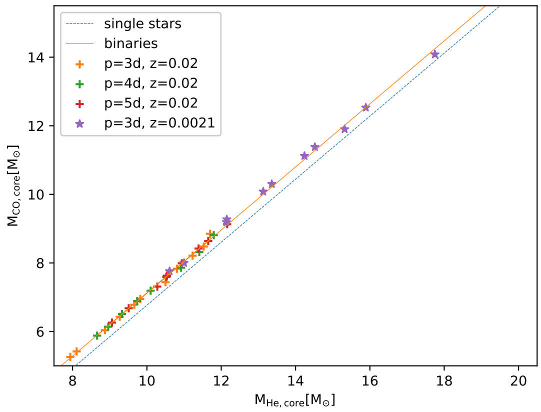

Fig. 5: The mass of the He and CO core for binary systems with an initial orbital period of 3, 4, and 5 days for metallicity $z = 0.02$ (Petrović 2022) and an initial orbital period of 3 days for $z = 0.0021$ from this paper. The solid line represents the fit for all binary systems and the dashed line for all single-star models.

If this assumption is used, we can estimate the black hole formation limit for each set of models. For the presented models with $z = 0.02$ and the initial orbital periods of 3 days, it is between 33 $M_\odot$ and 34 $M_\odot$. More precisely, from the presented linear fits for the CO core masses, we can obtain that the initial minimal primary masses needed for the black hole formation is 33.46 $M_\odot$. On the other side, based on the limit of 6.5 $M_\odot$, all primary stars with the SMC metallicity evolve into black holes. Also, secondary stars in all calculated binary models, for both metallicities, evolve into black holes. In summary, double compact objects resulting from our models are: 4 NS + BH (all with $z = 0.02$) and 18 double BH systems.

Petrović (2022) found that the correlation between the CO and helium core masses does not depend on the initial orbital period and can be approximated with the same linear fit for all binary systems considered in that paper. In this paper, we additionally show that the relation between the final helium and CO core masses does not depend on the metallicity either, and even more, there is only one linear correlation for all calculated binary systems in the range 30 $M_\odot$ - 40 $M_\odot$, presented by Petrović (2022) and in this paper. In the same way, there is only one linear correlation for all modeled single stars, for both metallicities:

$$M_{\rm CO} = 0.91898 M_{\rm He} - 2.42307. \tag{8}$$

Fig. 5 shows CO core masses as a function of final helium core masses for all calculated binary systems: orbital periods of 3, 4, and 5 days and metallicity of 0.02 and 0.0021. It is noticeable that there is no clear dependence on orbital period or metallicity, so, we can derive the following approximation:

$$M_{\rm CO} = 0.91922 M_{\rm He} - 2.06970. \tag{9}$$

We also confirm that the He/CO core masses ratio is slightly higher for primary stars evolving in binary systems than for the single star-counterparts.

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УТИЦАЈ МЕТАЛИЧНОСТИ НА МАСУ ХЕЛИЈУМСКОГ И УГЉЕНИЧНО-КИСЕОНИЧНОГ ЈЕЗГРА У МАСИВНИМ ЗВЕЗДАМА

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Оригинални научни рад

Представљамо резултате 58 детаљних еволуционих модела масивних усамљених и блиских двојних звезда са металичношћу Сунца и Малог Магелановог облака моделираних коришћењем MESA (Modules for Experiments in Stellar Astrophysics) нумеричког кода. Угљенично-кисеонична (CO) језгра усамљених звезда су у просеку 25% већа за металичност Малог Магелановог облака него за Сунчеву металичност. С друге стране, масе CO језгара примарних звезда у масивним двојним системима (са почетним орбиталим периодом од 3 дана и ефикасношћу акреције од 10%) су у просеку 50% веће за нижу вредност металичности. Граница за формирање црних рупа за примарне звезде са металичношћу Малог Магелановог облака је испод 30 $M_{\odot}$ и све примарне звезде са $z = 0.0021$, као и све секундарне звезде, завршавају своју еволуцију као црне рупе. Представљени еволуциони модели двојних система резултирају у 4 система неутронска звезда - црна рупа и 18 система двојних црних рупа. Такође је изведена релација између масе финалног хелијумског језгра и CO језгра и показано је да она не зависи од металичности. Потврђено је да је однос маса CO и хелијумског језгра већи код двојних система него у случају усамљених звезда.