Serb. Astron. J. № 205 (2022), 45 - 51
DOI: https://doi.org/10.2298/SAJ2205045P

UDC 52–423.4 : 524.387
Original scientific paper

THE INFLUENCE OF INITIAL ORBITAL PERIOD ON HELIUM AND CARBON-OXYGEN CORE MASSES IN MASSIVE CASE A BINARY SYSTEMS WITH LOW ACCRETION EFFICIENCY

Jelena Petrović

Astronomical Observatory, Volgina 7, 11000 Belgrade, Serbia
E–mail: *jpetrovic@aob.rs*

(Received: September 14, 2022; Accepted: November 8, 2022)

SUMMARY: The evolutionary models of 33 massive Case A binary systems in mass range from 30$M_\odot$ to 40$M_\odot$ with initial orbital periods of 3, 4 and 5 days, accretion efficiency of 10% and at the solar metallicity are presented. The models are obtained with the MESA (Modules for Experiments in Stellar Astrophysics) numerical code. The evolution is followed from a double O-type star, through Case A and Case AB mass transfer, to the formation of a carbon-oxygen (CO) core in the primary. The evolution of the secondary star in each binary system is further modeled with the same numerical code in an approximation of a single star, also to the formation of a carbon-oxygen core. The resulting helium core masses are in the range of 7.94$M_\odot$ - 13.19$M_\odot$ and 12.30$M_\odot$ and 19.12$M_\odot$ for primary and secondary stars, respectively. The carbon-oxygen core masses are between 5.26$M_\odot$ and 10$M_\odot$ for primaries and between 8.96$M_\odot$ and 15.32$M_\odot$ for secondaries. A clear influence of the initial orbital period on the resulting helium and CO core masses is demonstrated: primary stars in binary systems with initial orbital periods of 3, 4 and 5 days have on average about 15%, 8% and 2.5% smaller CO cores than single stars with the same initial masses. On the other hand, it was found that the correlation between the CO and helium core mass does not depend on the initial orbital period and can be approximated with the same linear fit for all binary systems. The CO/helium core mass ratio is found to be larger in binary systems than for single stars. It is also shown that the black hole formation limit for primary stars depends on the initial orbit and is between 33$M_\odot$ - 34$M_\odot$, 32$M_\odot$ - 33$M_\odot$ and 30$M_\odot$ - 31$M_\odot$, for the initial orbital periods of 3, 4 and 5 days, respectively. The resulting double compact objects are of two types: mixed neutron star - black hole systems (6 models) and double black holes (27 models). The resulting black hole masses are estimated to be in the range of 5$M_\odot$ to 17$M_\odot$.

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

1. INTRODUCTION

Double compact objects consisting of neutron stars and/or black holes are the result of evolution of massive binary systems, starting as double O-type stars and surviving two supernova explosions. Such systems go through multiple mass transfer phases and common envelope episodes that radically change the evolution and structure of each component. Depending on its initial mass, a massive star ends its evolution either as a neutron star (NS) or a black hole (BH). The minimum initial mass of a single star at the solar metallicity necessary for formation of an iron core is about 10 $M_\odot$ (Poelarends et al. 2008), while for binary systems this mass also depends on the initial orbital period and mass ratio (Wellstein et al. 2001).

If the initial binary system is very close (orbital period ≈ few days), the first mass transfer due to the Roche lobe overflow (RLOF) occurs while the primary is still a core hydrogen burning star. Such mass transfer is called Case A and it takes place on a thermal (fast phase) and a nuclear time scale (slow phase) of the stellar envelope (Petrovic et al. 2005, Sen et al. 2022). If mass transfer due to shell hydrogen burning occurs after Case A, it is called a Case AB mass transfer (Wellstein et al. 2001, Petrovic et al. 2005). After the helium core burning phase is completed, the star may expand again resulting in the third Roche lobe overflow and in the Case ABB mass transfer (Kippenhahn and Thomas 1970, Wellstein et al. 2001). During those interactions, the primary star loses most of its hydrogen rich envelope and produces a compact object in an Ib/c supernova explosion. Subsequently, the mass transfer from the secondary star to the newly-formed compact object will take place and the same loss of the hydrogen rich envelope may follow before the second compact object is formed.

The Case A evolution was previously linked to short period massive Wolf-Rayet+OB star binaries (Massey 1981, Niemela and Moffat 1982, Petrovic et al. 2005). Massive black hole binaries (Langer et al. 2020), supergiant X-ray binaries (Marchant et al. 2021) and Algol binaries (Sen et al. 2022) have also been associated with the Case A binary evolution. Massive Case A binaries were also related to a double compact object binary formation (Kruckow et al. 2018, Petrovic 2021, Schneider et al. 2021). Petrovic (2021) reported preliminary results on helium and carbon-oxygen core masses in Case A binary systems.

Mergers in Double Compact Objects (DCOs) have been recently associated with the emission of gravitational waves (GWs) by the observations of the LIGO and Virgo interferometers (Abbott et al. 2016a,b,c, 2019, 2021). The merging objects are the end product of stellar evolution in close binary systems: evolution that is significantly altered by interactions that change the physical properties of both stars and also their final fate. While it is known that the majority of massive binary systems evolve through interaction between components, the influence of those interactions on the resulting masses of neutron stars and black holes is still unclear.

In this paper we present evolutionary models of binary systems with initial masses in range between $30M_\odot$ and $40M_\odot$, with the mass ratio of 0.9, accretion efficiency of 10%. The initial orbital periods of 3, 4 and 5 days have been considered to investigate the influence of the initial orbit on the final helium and carbon-oxygen core masses.

The paper is structured as follows: the basics of numerical method are presented in Section 2. The details of evolutionary models are given in Section 3. Helium and CO core masses are presented in Section 4. The discussion is given in Section 5 and conclusions in Section 6.

2. NUMERICAL METHOD

The evolutionary models of non-rotating binary systems with primary star masses between $30M_\odot$ and $40M_\odot$ are obtained with the MESA (Modules for Experiments in Stellar Astrophysics) code (Paxton et al. 2011, 2013, 2015, 2018) in revision 10398. To investigate the influence of the initial orbit on the outcoming helium and carbon-oxygen core masses, three initial orbital periods were considered (3, 4 and 5 days) for metallicity of 0.02.

The calculated models cover the binary evolution from two massive O-type stars to the formation of a CO core in primaries. Soon after the formation of a CO core, the primaries complete their evolution into compact objects and further evolution of secondary stars is modeled in a single star approximation to the formation of the CO core, also with the MESA numerical code.

The initial mass ratio is set near 1, to avoid evolution of systems into a contact Wellstein et al. (2001). Low accretion efficiency was selected based on the work of Petrovic et al. (2005) that found this to be mostly in agreement with parameters of the observed Wolf-Rayet + O binaries. The initial primary masses were selected with the intention to investigate the black hole formation limit that was predicted in this range by Kruckow et al. (2018) and Petrovic (2021).

Ritter (1988) scheme is used for the calculation of mass transfer rate and the composition of accreted material is the same as the donor's current surface composition. Also, analyzed binary systems are assumed to be circularized due to tidal effects (Zahn 1977, Verbunt and Phinney 1995). Mass loss and angular momentum loss are due to stellar winds and non-conservative mass transfer. The stellar winds are included according to Vink et al. (2001) in the case of hydrogen surface abundance (X_s) above 0.4 and Nugis and Lamers (2000) with a scaling factor of 0.1 for hydrogen surface abundance below 0.4.

The specific angular momentum of the matter lost due to stellar wind is the same as the specific angular momentum of its star. Regarding the angular momentum loss due to non-conservative mass transfer, it is calculated according to Soberman et al. (1997) where a fixed fraction, in this case 90%, of the transferred mass is not accreted, but lost isotropically from the secondary star. The stellar wind mass loss is not included in the calculations when the central temperature in the primary star increases above $10^{8.2}$ K i.e. the core helium burning takes off.

Additionally , the evolution of single stars with initial masses between $30M_\odot$ and $75M_\odot$ is calculated for metallicity of 0.02 and 0.0021: between $30M_\odot$ and $40M_\odot$ with a step of $1M_\odot$ and between $40M_\odot$ and $75M_\odot$ with a step of $5M_\odot$. The stellar wind mass loss is also included based on Vink et al. (2001) for the main sequence evolution and Reimers (1975) for the red giant phase.

3. EVOLUTIONARY MODELS

Due to very short initial orbital periods, the primaries start transferring mass to their companions while they are still main sequence stars. At this time, helium cores in primary stars are not yet fully

Table 1: Evolutionary models with $z = 0.02$. $M_{1,\mathrm{in}}, M_{2,\mathrm{in}}$ - the initial primary and secondary mass, $M_{1,\mathrm{he}}, M_{1,\mathrm{co}}$ - the final helium core and CO core mass for the primary star, $M_{2,\mathrm{he}}, M_{2,\mathrm{co}}$ - the 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, except if marked with * where the value 0.05 is used.

$M_{1,\mathrm{in}}$	$M_{2,\mathrm{in}}$	$M_{1,\mathrm{he}}$	$M_{1,\mathrm{co}}$	$M_{2,\mathrm{he}}$	$M_{2,\mathrm{co}}$
$p_{in} =$	3 days				
30.0	27.0	7.94	5.26	12.30	8.96
31.0	27.9	8.10	5.42	13.72	10.33
32.0	28.8	8.84	6.06	13.99	10.57
33.0	29.7	9.25	6.43	14.90	11.40
34.0	30.6	9.65	6.78	15.85	12.29
35.0	31.5	9.82	6.95	14.88	11.40
36.0	32.4	10.48	7.44	16.87	13.21
37.0	33.3	10.80	7.83	16.79	13.03
38.0	34.2	11.22	8.21	18.48	14.64
39.0	35.1	11.52	8.48	17.24	13.56
40.0	36.0	11.69	8.85	16.97	13.37
$p_{in} =$	4 days				
30.0	27.0	8.66	5.88	12.78	9.38
31.0	27.9	8.96	6.14	13.81	10.42
32.0	28.8	9.33	6.51	13.94	10.52
33.0	29.7	9.74	6.89	13.78	10.30
34.0	30.6	10.10	7.19	14.94	11.47
35.0	31.5	10.52	7.59	15.88	12.19
36.0	32.4	10.92	7.86	16.54	12.93
37.0	33.3	11.41	8.32	17.15	13.47
38.0	34.2	11.80	8.81	18.04	14.29
39.0	35.1	12.19	8.94*	18.27	14.48
40.0	36.0	12.70	9.84*	19.12	15.32
$p_{in} =$	5 days				
30.0	27.0	9.06	6.26	12.83	9.50
31.0	27.9	9.51	6.68	13.56	10.21
32.0	28.8	10.53	7.60	14.59	11.10
33.0	29.7	10.28	7.31	14.80	11.30
34.0	30.6	10.55	7.63	15.62	12.08
35.0	31.5	10.94	7.99	15.91	12.35
36.0	32.4	11.39	8.42	16.89	13.16
37.0	33.3	11.65	8.64	17.31	13.63
38.0	34.2	12.16	9.13	18.61	14.79
39.0	35.1	13.19	9.49*	18.58	14.76
40.0	36.0	12.10	9.78*	18.00	14.19

formed. The closer the initial binary configuration, the less time for the primary stars to evolve detached and undisturbed by the binary interaction. Due to this, shorter initial orbital periods are correlated with lower helium and carbon-oxygen core masses.

The Case A mass transfer is closely followed by Case AB mass transfer with about 2 x 10^4 years in between. Primary stars expand due to the shell hydrogen burning and fill their Roche lobes again. The Case AB mass transfer lasts until the primaries shrink due to the onset of the helium core burning.

During the Case A + Case AB mass transfer, the primary stars lose large amount of their masses, about 15 - $20M_\odot$, and the secondary stars accrete about 10% of it. At the time of primary stars supernova explosions, the secondaries are still the main sequence stars with masses between $27M_\odot$ and $35M_\odot$.

After the explosion of the primary star, the further evolution of the secondary star includes mass transfer to the primary compact object, likely a common envelope phase, and the subsequent supernova explosion. Stellar evolution of secondary stars is further modeled in a single star approximation till the CO core is formed, also using the MESA numerical code. The resulting masses of helium and CO cores are given in Table 1.

Fig. 1 shows the HR diagram for both components of the $37.0M_\odot + 33.3M_\odot$ binary system with an initial orbital period of 3 days. The primary star (blue line) evolves off the main sequence, slowly increasing its radius and luminosity and decreasing its effective temperature. During the fast phase of Case A ($M_{\rm tr} \approx 10^{-4}M_\odot$/yr), the primary star decreases its luminosity and effective temperature, due to the large mass loss. It recovers slowly during the slow phase of Case A ($M_{\rm tr} \approx 10^{-6}M_\odot$/yr). Case AB causes a new decrease of luminosity and effective temperature. After the primary star ignites helium in its core, it starts shrinking and its effective temperature increases radically. At the same time the mass transfer to the secondary star stops. After all helium is exhausted in its core and carbon-oxygen core is formed, the primary starts expanding, because of the helium shell burning. The tracks are plotted until the onset of Case ABB mass transfer. The secondary star (red line) evolves off the main sequence and then significantly increases its luminosity due to mass gain. It continues its evolution as a rejuvenated, more massive main sequence star.

All other binary systems follow similar evolutionary paths. During the Case AB mass transfer, primary stars in all systems become WR stars with hydrogen surface abundance below 0.4 and their effective temperature increases to $10^{4.9}$ - $10^{4.96}$ K. After the helium core burning is completed, they expand again due to the ignition of helium in stellar envelopes.

The orbital period in modeled binary systems increases significantly during the presupernova evolution. Binary systems starting with an orbital period of 3 days have presupernova periods in the range of 23 - 27 days and the models starting evolution in a wider orbit - 4 and 5 days - end up with a presupernova orbital period in the range of 27 - 31 days and 24 - 36 days, respectively. If the system does not disrupt after the supernova explosion of the initially more massive star, it consists of a compact object (NS / BH) and a main sequence star.

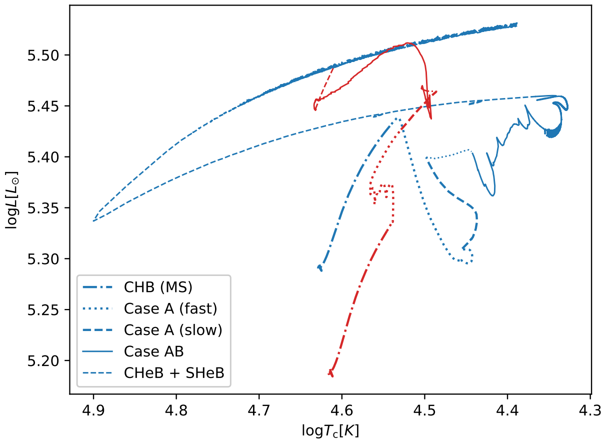

Fig. 1: The evolutionary tracks of the primary (blue line) and the secondary star (red line) in the $37.0M_\odot + 33.3M_\odot$ binary system with an initial orbital period of 3 days.

4. HELIUM AND CO CORE MASSES

Since the mass transfer in Case A binary systems starts before the end of hydrogen core burning, the resulting helium and CO core masses are lower than those for single stars. Fig. 2 shows the helium and CO core masses as a function of the initial mass for single stars and primary stars in the considered binary systems. It is clearly visible that the least massive helium and CO cores are formed in the initially closest binary systems, i.e. the ones with an initial orbital period of 3 days. Primary stars in binary systems with an initial orbital period of 3, 4 and 5 days have

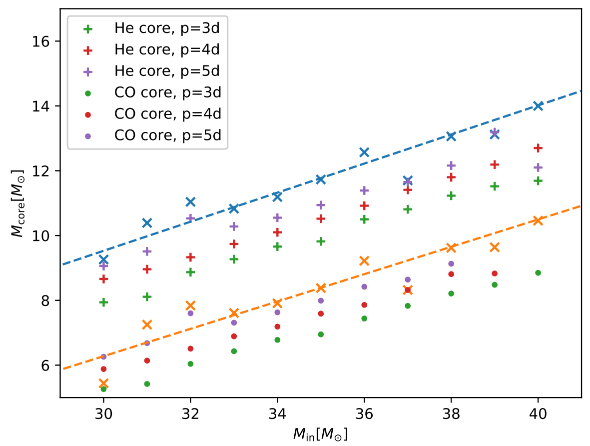

Fig. 2: Helium and carbon-oxygen core masses as a function of the initial stellar masses for primaries. The dashed lines represent linear fits for single stars.

on average about 15%, 8% and 2.5% smaller CO cores than single stars with the same initial masses.

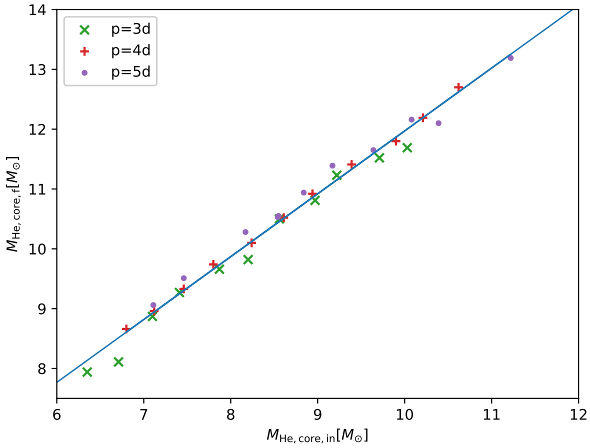

Fig. 3: The final helium core mass at the moment of helium exhaustion as a function of the initial helium core mass in primary stars.

Fig. 3 shows the mass of the final helium core as a function of the initial helium core mass for primary stars in all calculated models. The initial helium core mass is defined as the mass of the helium core at the moment all hydrogen is exhausted in the stellar core. The final helium core mass is defined as the helium core mass when the helium core burning is completed. It is noticeable that there is no clear dependence on the initial orbital period. So, we can derive the following approximation valid for all presented binary systems:

$$M_{\mathrm{He,f}} = 1.05074 M_{\mathrm{He,i}} + 1.46333\,, \tag{1}$$

where $M_{\mathrm{He,f}}$ is the mass of the final and $M_{\mathrm{He,i}}$ the mass of the initial helium core for primary stars.

Fig. 4 presents CO core mass as a function of the final helium core mass for single stars and primary stars in the considered binary systems. It shows that the correlation between the CO core mass and the final helium core mass also does not depend on the initial orbital period. It is also visible that the CO/helium core mass ratio is larger in primaries evolving within binary systems than for single stars.

The linear approximation for primary stars is:

$$M_{\mathrm{CO}} = 0.91917 M_{\mathrm{He}} - 2.08267\,. \tag{2}$$

At the same time, the fit for all single stars modeled in this paper is:

$$M_{\mathrm{CO}} = 0.94086 M_{\mathrm{He}} - 2.69178\,. \tag{3}$$

All helium and CO core masses are given in Table 1. Primary helium core masses are in the range of $7.94 M_\odot$ - $13.19 M_\odot$ and CO core masses in range of $5.26 M_\odot$ to almost $10 M_\odot$. As already mentioned, as the primary reaches the CO core formation, the

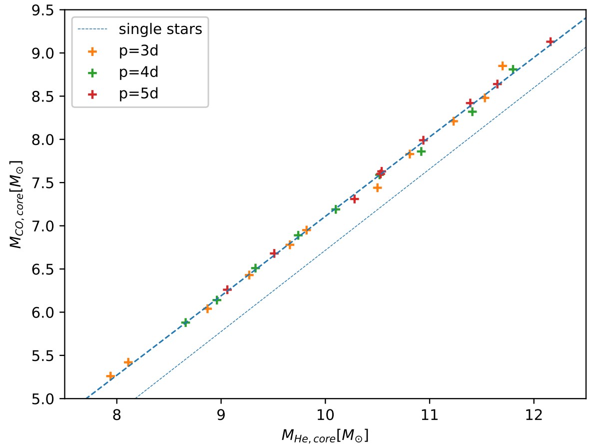

Fig. 4: The CO core mass as a function of the final helium core mass for single stars and primary stars in the considered binary systems.

calculation of the binary evolution is completed and further evolution of the secondary star is then modeled as an evolution of a single star, also until the formation of the CO core. Helium core masses of secondary stars are between $12.30 M_\odot$ and $19.12 M_\odot$ and CO core masses are in the range $8.96 M_\odot$ - $15.32 M_\odot$.

5. DISCUSSION

To put calculated helium and CO core masses in a context of a possible outcome (NS or BH), the limit by Tauris et al. (2015) is used. According to this criterium, an iron-core collapse supernova results in a neutron star if the CO core has a mass between $1.435 M_\odot$ and $6.5 M_\odot$. If the carbon-oxygen core mass is above $6.5 M_\odot$, then a black hole is formed. In our models the primary stars are stripped of their hydrogen envelopes almost entirely. The mass of the hydrogen envelope that is left after two mass transfers (Case A and Case AB) and stellar wind mass loss are in the range of $0.3 M_\odot$ - $0.4 M_\odot$. Since the stellar wind is not included in calculations during the Case AB mass transfer, we can safely assume that the final hydrogen envelope masses are even lower, qualifying for the envelope mass limit for stripped stars given by Tauris et al. (2015) as $0.2 M_\odot$. We assumed the same for secondary stars, since those will most likely be stripped as well in a common envelope phase.

If this assumption is used, we can estimate the black hole formation limit for each set of models. As we mentioned, the first mass transfer starts during the helium core formation, and the black hole formation limit depends on the initial orbital period. For the initial orbital periods of 3, 4 and 5 days this limit is between $33 M_\odot$ - $34 M_\odot$, $32 M_\odot$ - $33 M_\odot$ and $30 M_\odot$ - $31 M_\odot$, respectively. Based on the criterium of $6.5 M_\odot$, all secondary stars evolve into black holes.

The obtained black hole formation limits for primary stars are in the line with the population synthesis results presented by Kruckow et al. (2018) which showed that the black hole formation limit is around 33 $M_{\odot}$. They also showed that binaries with initial masses of $30M_{\odot}$ - $40M_{\odot}$ and a mass ratio near one can be progenitors of NS + BH compact objects, which is also confirmed with our models. The double compact objects resulting from our models are: 6 NS + BH and 27 double BH systems. Based on the estimate of the masses of compact remnants by Belczynski et al. (2008, 2010), we obtain black hole masses in the range of $5M_{\odot}$ - $12M_{\odot}$ for primary stars and $12M_{\odot}$ - $17M_{\odot}$ for secondary stars with mass ratios from 0.43 to 0.74.

6. CONCLUSIONS

This paper presents detailed evolutionary models of close massive binary systems calculated with the MESA numerical code. The initial conditions are: $30M_{\odot}$ - $40M_{\odot}$ primaries, a mass ratio of 0.9, orbital periods of 3, 4 and 5 days, and solar metallicity. The evolution of binary systems is calculated through the Case A and Case AB mass transfer, to the CO core formation in primaries. The carbon-oxygen core masses of secondary stars are calculated via a single star evolution.

In comparison with single stars, primary stars in binary systems with the same initial mass develop less massive helium and CO cores, in other words, the black hole formation limit for primary stars depends on the initial orbit. This is a consequence of an enormous mass loss due to mass transfer before the helium core is fully formed in those stars. Our models also show that the initial orbital period increase makes the resulting helium and CO core masses closer to the single star results. This means that the helium and CO cores produced via the late Case A mass transfer channel would be very similar to the ones resulting from the single star evolution. On the other hand, the correlation between the CO and helium core mass does not depend on the initial period. The final CO/He core mass ratio in binaries is slightly larger than for single stars.

Acknowledgements – During work on this paper, J. Petrovic was financially supported by the Ministry of Education and Science of the Republic of Serbia through contract 451-03-9/2022-14/200002.

REFERENCES

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016a, PhRvL, 116, 061102
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016b, PhRvL, 116, 241103
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016c, ApJL, 818, L22
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2019, PhRvX, 9, 031040
Abbott, R., Abbott, T. D., Abraham, S., et al. 2021, PhRvX, 11, 021053
Belczynski, K., Kalogera, V., Rasio, F. A., et al. 2008, ApJS, 174, 223
Belczynski, K., Bulik, T., Fryer, C. L., et al. 2010, ApJ, 714, 1217
Kippenhahn, R. and Thomas, H. -C. 1970, in IAU Colloq. 4: Stellar Rotation, ed. A. Slettebak, 20
Kruckow, M. U., Tauris, T. M., Langer, N., Kramer, M. and Izzard, R. G. 2018, MNRAS, 481, 1908
Langer, N., Schürmann, C., Stoll, K., et al. 2020, A&A, 638, A39
Marchant, P., Pappas, K. M. W., Gallegos-Garcia, M., et al. 2021, A&A, 650, A107
Massey, P. 1981, ApJ, 244, 157
Niemela, V. S. and Moffat, A. F. J. 1982, ApJ, 259, 213
Nugis, T. and Lamers, H. J. G. L. M. 2000, A&A, 360, 227
Paxton, B., Bildsten, L., Dotter, A., et al. 2011, ApJS, 192, 3
Paxton, B., Cantiello, M., Arras, P., et al. 2013, ApJS, 208, 4
Paxton, B., Marchant, P., Schwab, J., et al. 2015, ApJS, 220, 15
Paxton, B., Schwab, J., Bauer, E. B., et al. 2018, ApJS, 234, 34
Petrovic, J. 2021, Eur. Phys. J. D, 75, 162
Petrovic, J., Langer, N. and van der Hucht, K. A. 2005, A&A, 435, 1013
Poelarends, A. J. T., Herwig, F., Langer, N. and Heger, A. 2008, ApJ, 675, 614
Reimers, D. 1975, Problems in Stellar Atmospheres and Envelopes (Springer), 225
Ritter, H. 1988, A&A, 202, 93
Schneider, F. R. N., Podsiadlowski, P. and Müller, B. 2021, A&A, 645, A5
Sen, K., Langer, N., Marchant, P., et al. 2022, A&A, 659, A98
Soberman, G. E., Phinney, E. S. and van den Heuvel, E. P. J. 1997, A&A, 327, 620
Tauris, T. M., Langer, N. and Podsiadlowski, P. 2015, MNRAS, 451, 2123
Verbunt, F. and Phinney, E. S. 1995, A&A, 296, 709
Vink, J. S., de Koter, A. and Lamers, H. J. G. L. M. 2001, A&A, 369, 574
Wellstein, S., Langer, N. and Braun, H. 2001, A&A, 369, 939
Zahn, J. -P. 1977, A&A, 57, 383

УТИЦАЈ ПОЧЕТНОГ ОРБИТАЛНОГ ПЕРИОДА НА МАСУ ХЕЛИЈУМСКОГ И УГЉЕНИЧНО-КИСЕОНИЧНОГ ЈЕЗГРА У БЛИСКИМ МАСИВНИМ ДВОЈНИМ СИСТЕМИМА СА НИСКОМ ЕФИКАСНОШЋУ АКРЕЦИЈЕ

Jelena Petrović

Astronomical Observatory, Volgina 7, 11000 Belgrade, Serbia

E–mail: *jpetrovic@aob.rs*

УДК 52–423.4 : 524.387

Оригинални научни рад

У овом раду су представљени еволуциони модели масивних двојних система са масама од $30M_{\odot}$ до $40M_{\odot}$, орбиталним периодима од 3, 4 и 5 дана, ефикасношћу акреције од 10% и соларном металичношћу. Модели су направљени са MESA (Modules for Experiments in Stellar Astrophysics) нумеричким кодом. Еволуција је праћена од главног низа, кроз два трансфера масе (Case A, Case AB) до формирања угљенично - кисеоничног (CO) језгра у примарној звезди. Еволуција секундарне звезде је моделирана даље у апроксимацији усамљене звезде, такође до формирања CO језгра. Масе хелијумских језгара су између $7.94M_{\odot}$ и $13.19M_{\odot}$ и $12.30M_{\odot}$ и $19.12M_{\odot}$ за примарне и секундарне звезде, респективно. Масе CO језгара су од $5.26M_{\odot}$ до $10M_{\odot}$ за примарне и од $8.96M_{\odot}$ до $15.32M_{\odot}$ за секундарне звезде. Примарне звезде у двојним системима са почетним орбиталним периодима од 3, 4 и 5 дана имају у просеку 15%, 8% и 2.5% мања CO језгра од усамљених звезда истих почетних маса. С друге стране, почетни орбитални период не утиче на корелацију између почетне и крајње масе хелијумског језгра, нити на корелацију масе CO језгра и масе хелијумског језгра код примарних звезда. Лимит за формирање црне рупе од примарне звезде зависи од почетног орбиталног периода и установљен је између $33M_{\odot}$ - $34M_{\odot}$, $32M_{\odot}$ - $33M_{\odot}$ и $30M_{\odot}$ - $31M_{\odot}$ за почетне орбиталне периоде од 3, 4 и 5 дана, респективно. Дупли компактни објекти који произлазе из представљених модела су: 6 система који се састоје од неутронске звезде и црне рупе и 27 система који се састоје од две црне рупе. Процењене масе црних рупа које произлазе из представљених модела су између $5M_{\odot}$ и $17M_{\odot}$.