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Abstract

J1846-0513 is a millisecond pulsar binary discovered by the Five-hundred-meter Aperture Spherical radio Telescope (FAST), a Chinese independently developed facility. Data analysis yields an orbital period of P_{orb}=0.613,d and an orbital eccentricity of e=0.208. According to binary evolution theory, the orbital eccentricity of this system most likely formed during the supernova explosion of the companion star that created the neutron star. Based on mass parameters, this system is identified as a double neutron star candidate. Given that the progenitor evolution of this system is of great significance for understanding stellar and binary evolution, we have used a stellar evolution code to simulate the evolution of a binary system composed of a neutron star with an initial mass of 1.345,{M}*{ } and a helium star with an initial mass of 2.8,{M}*{ }, with an initial orbital period of 0.5,d. The simulation shows that the helium star mass ultimately decreases to 1.554,{M}*{ }, with a carbon-oxygen core mass of 1.431,{M}*{ }. At the end of evolution, the helium star center develops a silicon core of approximately 0.846,{M}*{ } and an iron core of approximately 0.086,{M}*{ } along with neutron-rich nuclei, indicating that this helium star will undergo an iron-core-collapse supernova explosion, forming a neutron star with mass close to the observed lower limit. Simulations of the abrupt orbital change of the binary system caused by the supernova explosion demonstrate that this model can evolve into the observed elliptical-orbit double neutron star candidate.

Full Text

Progenitor Evolution of the Double Neutron Star System J1846-0513

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Abstract

J1846-0513 is a millisecond pulsar binary discovered by China’ s Five-hundred-meter Aperture Spherical radio Telescope (FAST). Observational data analysis yields an orbital period of $P_{\mathrm{orb}} = 0.613$ d and an orbital eccentricity of $e = 0.208$. According to binary evolution theory, this eccentricity most likely formed during the supernova explosion in which the companion star collapsed to form a neutron star. Based on mass parameters, the system is identified as a double neutron star candidate. Given the importance of this system’ s progenitor evolution for understanding stellar and binary evolution, we have used a stellar evolution code to simulate the evolution of a binary system composed of a neutron star with initial mass $1.345 M_{\odot}$ and a helium star with initial mass $2.8 M_{\odot}$, with an initial orbital period of 0.5 d. The simulation shows that the helium star’ s mass ultimately decreases to $1.554 M_{\odot}$, with a carbon-oxygen core mass of $1.431 M_{\odot}$. At the end of the evolution, the helium star develops a silicon core of approximately $0.846 M_{\odot}$ and an iron/neutron-rich core of approximately $0.086 M_{\odot}$, indicating that the helium star will undergo an iron-core collapse supernova, forming a neutron star with mass close to the observed lower limit. Simulations of the orbital disruption caused by the supernova explosion demonstrate that this model can evolve into the observed eccentric double neutron star candidate.

Key words stars: evolution, stars: neutron, binaries: general, stars: individual: PSR J1846-0513

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1 Introduction

Since Hulse and Taylor discovered the first double neutron star system B1913+16 in 1975 [?], approximately 30 double neutron star candidate systems have been observed, two-thirds of which have been confirmed [?]. The gravitational wave signal GW170817 produced by the merger of a double neutron star system triggered the first multi-messenger astronomical observation, including gravitational waves, radio, infrared, optical, ultraviolet, X-ray, and gamma-ray emissions [?]. Given the significance of double neutron star systems for astrophysical and fundamental physics research, numerous studies have investigated their formation processes and subsequent evolution. In 1975, Flannery and van den Heuvel proposed that the “kick” imparted to the newly formed neutron star by asymmetries in the supernova explosion process created the orbital eccentricity of B1913+16 [?]. In 1983, Hills conducted a complete theoretical analysis of how mass loss and kicks during supernova explosions affect binary system orbits [?]. Since then, other researchers have comprehensively and thoroughly discussed the effects of supernova explosion processes and kicks [?, ?, ?, ?, ?, ?, ?, ?, ?].

Beyond dynamical considerations, research on stellar and binary evolution theory related to double neutron stars has also advanced considerably. In 2013, Tauris et al. [?] studied the evolution of a binary system composed of a $1.35M_\odot$ neutron star and a $2.9M_\odot$ helium star, simulating the helium star to the oxygen ignition stage approximately ten years before the supernova explosion. In 2015, Tauris et al. [?] simulated a series of neutron star-helium star binaries, following helium star evolution until before silicon burning. In 2017, Tauris et al. [?] combined observational data from known double neutron star systems to discuss various aspects of their formation and evolution, including correlations between recycled pulsar spin periods and binary orbital periods, and the possibility of forming observed double neutron star systems through supernova explosions with specific orbital periods and eccentricities. Moriya et al. [?] used the large-scale stellar evolution code Modules for Experiments in Stellar Astrophysics (MESA) [?, ?, ?, ?] to simulate the evolution of single helium stars with given mass loss processes until core-collapse supernova, approximating the progenitor evolution of double neutron star systems. To discuss the formation of the progenitor system of gravitational wave GW170817, Jiang et al. [?] used MESA' s binary evolution module (MESA binary) to simulate neutron star-helium star binary evolution until iron core fallback in the helium star (fallback velocity reaching 1000 km s^{-1}).

Considering that when the mass of a degenerate oxygen-neon core approaches the Chandrasekhar limit, electron-capture reactions on ^{24}Mg and ^{20}Ne may trigger supernova explosions, forming neutron stars [?, ?, ?, ?] (i.e., electron-capture supernovae, EC-SN), Guo et al. [?] investigated the initial parameter space for neutron star-helium star binaries forming double neutron stars through electron-capture supernovae, providing the boundary between electron-capture and iron-core collapse channels for double neutron star formation.

China' s Five-hundred-meter Aperture Spherical radio Telescope (FAST) has provided substantial observational data and achieved numerous important results since its commissioning. To date, FAST has discovered over 1000 radio pulsars, including nearly 200 millisecond pulsars, more than 100 faint intermittent pulsars, and three double neutron star candidate systems: J2150+3427 [?], J1901+0658 [?], and J1846-0513 [?] (hereafter J1846). Timing analysis of over two years of data for the J1846 system reveals: pulsar spin period $P_s = 23.36$ ms, characteristic age 366.16 Myr, surface magnetic field strength 4.92×10^9 G; binary orbital period $P_{\rm orb} = 0.613$ d, orbital eccentricity 0.208; total binary system mass $(2.6287 \pm 0.0035)M_\odot$; pulsar mass upper limit $1.3455M_\odot$, companion mass lower limit $1.2845M_\odot$. Clearly, this pulsar is a recycled pulsar, and its companion is most likely a young, normal neutron star [?].

Considering the importance of J1846' s progenitor evolution for understanding binary evolution and double neutron star system formation, Jiang et al. [?] used the MESA code to simulate three neutron star-helium star binary evolution processes until iron core fallback in the helium star, reproducing the progenitor evolution of J1846. The three systems had zero-age helium main-sequence (He ZAMS) initial masses of 3.3, 3.5, and $4.0 M_{\odot}$, respectively, with the resulting second neutron star mass range of $1.34-1.39 M_{\odot}$ based on the helium star’ s final state, slightly above the observed mass lower limit of J1846’ s companion. To obtain a neutron star mass closer to the observed lower limit of J1846’ s companion, discuss the evolution near the mass lower limit for iron-core collapse supernovae, and deepen our understanding of stellar and binary evolution, this work uses MESA binary to simulate the evolution of neutron star-helium star binary systems, conducting further research on the progenitor evolution of J1846.

Section 2 of this paper introduces the binary evolution code and parameter settings; Section 3 discusses the simulation results in detail, including binary orbital evolution and helium star evolution; Section 4 discusses the subsequent evolution of the helium star, the impact of supernova explosion on the binary system, and the possibility of system merger within a Hubble time; Section 5 summarizes this work.

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2 Simulation Program and Parameter Settings

MESA is a large-scale one-dimensional stellar evolution program that has developed through hundreds of versions. Its single-star module (star) can simulate the complete evolution of a star from pre-main-sequence to supernova explosion [?, ?, ?, ?], while the binary module (binary) builds upon the single-star module to simulate various binary evolution processes, with results widely recognized. This work uses the binary module in MESA version r12778 to simulate the evolution of binary systems composed of a neutron star and a helium star. To facilitate comparison with observational data for J1846, the initial neutron star mass ($M_{\mathrm{NS,1}}$) is set to $1.345 M_{\odot}$. Considering the results of Guo et al. [?], the initial helium star companion mass (M_{He}) is set to $2.8 M_{\odot}$, with composition: helium mass fraction 98%, heavy element mass fraction 2%, i.e., $Y=0.98$, $Z=0.02$ (hydrogen mass fraction zero, $X=0$). The binary begins in a circular orbit with initial orbital period $P_{\mathrm{orb,i}}=0.5$ d. To account for neutrino processes that may be involved in the late evolution of the helium star, Guo et al. [?] used the nuclear reaction network weak.net with 43 participating isotopes; Moriya et al. [?] used MESA151.net containing 151 isotopes; Jiang et al. [?, ?, ?] used MESA235.net containing 235 isotopes. To avoid bias from insufficient isotope species, this work merged these three networks to obtain a network containing 241 isotopes. Following Langer’ s recommendation [?], the helium star’ s mixing length parameter is set to $\alpha=l/H_p=1.5$, where l is the mixing length and H_p is the local pressure scale height. Mass loss due to helium star winds adopts the “Dutch” prescription [?], with scaling parameter set to 1 and opacity set to Type 2. The simulation neglects wind accretion onto the neutron star, assuming that companion wind material leaves the system carrying the helium star’ s specific orbital angular momentum.

Due to the small binary orbital separation, the helium star will fill its Roche lobe during evolution, causing material to flow through the inner Lagrange point to the neutron star, resulting in case BB Roche Lobe Overflow (RLO). This work adopts the optically thick model for mass transfer caused by Roche lobe overflow proposed by Kolb and Ritter in 1990 [**?**]. Since the mass transfer rate caused by case BB RLO in helium stars far exceeds the neutron star' s Eddington limit accretion rate ($|\dot{M}_{\mathrm{He}}| \gg \dot{M}_{\mathrm{Edd}}$), most material will leave the system as isotropic wind from near the neutron star, carrying away the neutron star' s specific orbital angular momentum [**?**, **?**, **?**]. Considering the short evolutionary timescale of the helium star and that the neutron star mass does not change significantly (increase less than $0.001 M_{\odot}$), this work sets the Eddington limit accretion rate as a fixed value: $\dot{M}_{\mathrm{Edd}} = 3.0 \times 10^{-8} M_{\odot}\,\mathrm{yr}^{-1}$.

Additionally, considering convective mixing, we set: when the evolution timestep exceeds 1 yr, elemental diffusion effects cannot be neglected, and diffusion calculations adopt the results given by Stanton and Murillo in 2016 [**?**].

Considering that the evolution from helium main-sequence star to pre-supernova involves a vast range of temperature, density, and pressure changes in the stellar core, this evolutionary process is simulated in two stages. Stage 1 runs from zero-age helium main-sequence to core carbon burning and neon core formation. During this stage, the core temperature rises to approximately $10^{8.8}$ K, the core carbon abundance drops below 0.2%, and less than 100 yr of evolution remains until core collapse. Stage 2 continues the binary evolution after changing the simulation configuration file (change inlist) until a silicon core with significant mass forms in the helium star, ensuring the helium star cannot undergo an electron-capture supernova but instead enters the evolutionary stage preceding iron-core collapse supernova. Except for the parameters mentioned above, the configuration files for Stage 1 and Stage 2 in this work are consistent with Jiang et al. [**?**, **?**, **?**].

3.1 Evolution of the Binary Orbital Period

Simulation results show that after approximately two million years of evolution, the helium star loses about half its mass, decreasing to $1.554 M_{\odot}$, while the neutron star accretes only about $6.8 \times 10^{-4} M_{\odot}$ of companion material. The evolution of the binary orbital period is shown in Figure 1 [Figure 1: see original paper]. The horizontal axis represents the logarithm of remaining evolution time: $\lg[(t_* - t)/\mathrm{yr}]$, where $t_* \simeq 2.17 \times 10^6$ yr is the total evolution timescale and t is the stellar age measured from helium zero-age main-sequence. The figure shows that the binary system first undergoes a phase of slowly increasing orbital period, which occupies most of the binary evolution, until the remaining time is about $10^{4.5}$ yr, when the orbital period grows from 0.5 d to about 0.59 d. Subsequently, the binary orbit rapidly contracts, and after approximately

8000 years of evolution, at $\lg[(t_* - t)/\mathrm{yr}] \simeq 4.395$, the orbital period contracts again to about 0.5 d. Thereafter, the binary system experiences a second orbital expansion, with the final orbital period expanding to approximately 0.53 d.

To understand the orbital evolution, theoretical analysis is required. Neglecting the spin angular momentum of the binary components, the system' s orbital angular momentum can be expressed as $J = \mu a^2 \Omega$, where $\mu = M_{\mathrm{He}} M_{\mathrm{NS},1}/(M_{\mathrm{He}} + M_{\mathrm{NS},1})$ is the reduced mass of the binary system, a is the binary separation, and $\Omega = 2\pi/P_{\mathrm{orb}}$ is the angular velocity of the binary' s mutual orbit. Combining this with Kepler' s third law yields the differential equation satisfied by the orbital period change rate:

$$\frac{\dot{P}_{\mathrm{orb}}}{P_{\mathrm{orb}}} = \frac{\dot{M}_{\mathrm{NS},1}}{M_{\mathrm{NS},1}} + \frac{\dot{M}_{\mathrm{He}}}{M_{\mathrm{He}}} - \frac{3\dot{a}}{a} = \frac{\dot{M}_{\mathrm{NS},1}}{M_{\mathrm{NS},1}} + \frac{\dot{M}_{\mathrm{He}}}{M_{\mathrm{He}}} - \frac{3\dot{J}}{J} + \frac{3\dot{M}_{\mathrm{tot}}}{2M_{\mathrm{tot}}}$$

where $M_{\mathrm{tot}} = M_{\mathrm{He}} + M_{\mathrm{NS},1}$ is the total binary mass. In our model, the helium star's mass loss rate is shown in Figure 2 [Figure 2: see original paper]. The mass loss rates driven by stellar wind ($\dot{M}_{\mathrm{wind}}$) and Roche lobe overflow ($\dot{M}_{\mathrm{RLO}}$) are indicated by green dot-dashed and red short-dotted lines, respectively, while the total mass loss rate ($\dot{M}_{\mathrm{He}}$) is shown by the blue dashed line. The gray vertical dotted line marks the transition between Stage 1 and Stage 2, i.e., the time when the configuration file is changed. The horizontal gray dotted line represents the neutron star' s constant Eddington limit accretion rate: $\dot{M}_{\mathrm{Edd}} = 3.0 \times 10^{-8} M_\odot\,\mathrm{yr}^{-1}$. The figure shows that stellar wind-driven mass loss dominates the early orbital evolution, while at $\lg[(t_* - t)/\mathrm{yr}] \approx 4.5$, Roche lobe overflow begins and quickly exceeds wind mass loss. Whether dominated by wind mass loss in the early phase (where the blue dashed line coincides with the green dot-dashed line) or by Roche lobe overflow in the late phase (where the blue dashed line coincides with the red short-dotted line), the helium star' s mass loss rate far exceeds the neutron star' s Eddington limit accretion rate ($|\dot{M}_{\mathrm{He}}| \gg \dot{M}_{\mathrm{NS},1}$), making neutron star accretion negligible. Therefore, the differential equation (1) simplifies to:

$$\frac{\dot{P}_{\mathrm{orb}}}{P_{\mathrm{orb}}} \simeq \frac{\dot{M}_{\mathrm{He}}}{M_{\mathrm{He}}} - \frac{3\dot{J}}{J}$$

Since angular momentum loss $\dot{J} < 0$ is also caused by mass loss, the system' s orbital angular momentum loss rate can be expressed as:

$$\frac{\dot{J}}{J} = \frac{q}{1+q}\frac{\dot{M}_{\mathrm{wind}}}{M_{\mathrm{He}}} + \frac{\dot{M}_{\mathrm{RLO}}}{(1+q)M_{\mathrm{He}}}$$

where $q = M_{\mathrm{NS},1}/M_{\mathrm{He}}$. The first term represents orbital angular momentum carried away by wind leaving the helium star surface, while the second term represents angular momentum carried away by mass loss due to Roche lobe overflow from near the neutron star surface. Before Roche lobe overflow occurs, $\dot{M}_{\rm He} = \dot{M}_{\rm wind}$, and only the first term operates, reducing the orbital period change rate to:

$$\frac{\dot{P}_{\rm orb}}{P_{\rm orb}} \simeq -\frac{2}{1+q}\frac{\dot{M}_{\rm He}}{M_{\rm He}}$$

Since $\dot{M}_{\rm He} < 0$, this equation shows that helium star wind mass loss always causes binary orbital expansion. After Roche lobe overflow begins, $\dot{M}_{\rm RLO} \gg \dot{M}_{\rm wind}$ and $\dot{M}_{\rm He} \simeq \dot{M}_{\rm RLO}$, the first term in equation (3) can be neglected, and the orbital period change rate becomes:

$$\frac{\dot{P}_{\rm orb}}{P_{\rm orb}} \simeq \frac{3-2q-3q^2}{q(1+q)}\frac{\dot{M}_{\rm He}}{M_{\rm He}}$$

This equation shows that when q is relatively small, the binary orbit expands, and when q is relatively large, the orbit contracts. Setting $\dot{P}_{\rm orb} = 0$ yields the critical mass ratio $q_c = (\sqrt{10}-1)/3 \simeq 0.721$, corresponding to a helium star mass of about $1.867 M_\odot$, consistent with the helium star mass at the beginning of the second orbital growth phase in the evolution track.

3.2 Evolution of the Helium Star

Figure 3 [Figure 3: see original paper] shows the evolution of the helium star’ s structure. The red dashed line shows the evolution of the helium star’ s total mass, while the blue dot-dashed, green dotted, and black solid lines show the evolution of the carbon core mass, oxygen core mass, and silicon core mass, respectively. The gray vertical dotted line corresponds to the time when the stellar evolution configuration file is changed. The figure shows that at the end of evolution, the helium star’ s total mass decreases to $1.554 M_\odot$, the central silicon core mass reaches $0.846 M_\odot$, and the oxygen and carbon core masses reach $1.345 M_\odot$ and $1.431 M_\odot$, respectively. The simulation results also show that at $\lg[(t_* - t)/{\rm yr}] \simeq -9$, a neutron-rich core with mass about $0.086 M_\odot$ and an iron core with mass $0.0863 M_\odot$ appear in the helium star interior. The neutron-rich core mass is slightly larger than the iron core, and it appears slightly earlier than the iron core, indicating that electron-capture reactions occur slightly earlier than silicon burning in the central region, a situation that also occurred in Jiang et al.’ s simulations [**?**].

It should be noted that different core mass definitions yield slightly different results. The MESA program provides multiple definition methods, each with its advantages (reasonableness) and shortcomings. Here, the silicon and iron core masses are defined as the mass coordinates corresponding to the outermost shells where ^{28}Si and ^{56}Fe dominate, respectively. The carbon and oxygen core masses are defined differently: the carbon core mass is defined as the mass coordinate of the shell where the ^{4}He mass fraction first drops below 0.01 when moving inward, and similarly, the oxygen core mass is defined as the mass coordinate where the ^{12}C mass fraction first drops below 0.01. Additionally, this critical mass fraction could take other values, such as 0.05.

The evolution curves show that the carbon core appears at $\lg[(t_* - t)/\mathrm{yr}] \simeq 5.22$; the oxygen core appears at $\lg[(t_* - t)/\mathrm{yr}] \simeq 3.77$, and its mass increases rapidly at and after $\lg[(t_* - t)/\mathrm{yr}] \simeq 2.95$; the silicon core appears at $\lg[(t_* - t)/\mathrm{yr}] \simeq 0.72$ and reaches its maximum mass at $\lg[(t_* - t)/\mathrm{yr}] \simeq 0.25$. It should be noted that before the silicon core mass reaches its maximum, there is an obvious fluctuation near $\lg[(t_* - t)/\mathrm{yr}] \simeq 0.25$: it first drops to zero, then rapidly increases to the maximum. This variation is not caused by real physical reasons but rather by the aforementioned shortcomings of the silicon core mass definition. In fact, using other definitions would cause similar fluctuations, though different definitions would produce fluctuations of different magnitudes and at different locations. For example, in Jiang et al.' s work on black hole-neutron star gravitational wave source progenitor evolution [?], the silicon core mass was defined using the mass coordinate where the ^{16}O mass fraction first drops below 0.05. In their third simulated system (Sys. C), when the iron core mass grew to about $1.4M_\odot$, the silicon core mass suddenly dropped to zero and remained there until the end of the simulation.

Comparing with Figure 2 reveals that the helium star' s mass loss rate changes dramatically near the aforementioned time points. For instance, the rapid increase in oxygen core mass at $\lg[(t_* - t)/\mathrm{yr}] \simeq 2.95$ occurs just after mass loss due to Roche lobe overflow. When the silicon core mass reaches its maximum at $\lg[(t_* - t)/\mathrm{yr}] \simeq 0.25$, there are corresponding fluctuations in the Roche lobe overflow mass loss curve and small changes in wind-driven mass loss. The physics behind these correlations has been elaborated in Jiang et al. [?] and will not be repeated here.

Figure 4 [Figure 4: see original paper] shows the evolution of the helium star' s surface luminosity with effective temperature (evolution on the Hertzsprung-Russell diagram), while Figure 5 [Figure 5: see original paper] shows the evolution of the stellar interior density-temperature relation. In both figures, red open circles mark the end of central helium burning (i.e., the end of helium main-sequence, He-MS), red triangles mark the configuration file change point, stars mark the beginning of Roche lobe overflow, and squares mark the position where the helium star' s central silicon core appears ($M_{\mathrm{Si}} > 0$). The inset in Figure 4 shows details of the evolution track near the configuration file change position. Arrows and numbered labels in both the main panel and inset of Figure 4 indicate the evolution direction and sequence. In Figure 5, gray dashed, dotted, dot-dashed, and solid lines represent the ignition conditions for silicon, oxygen, neon, and carbon, respectively.

The data show that after approximately 2.05×10^6 yr of evolution, when the remaining time is about $\lg[(t_* - t)/\mathrm{yr}] \simeq 5.08$, the central helium is exhausted, He-MS evolution ends, the stellar surface temperature reaches a maximum of about $10^{4.99}$ K, and the corresponding luminosity reaches about $10^{4.02}L_\odot$. At this time, the helium star has not yet filled its Roche lobe. Subsequently, as shell helium burning proceeds, the stellar envelope expands rapidly, the surface temperature decreases, and the helium star evolves to the giant branch. While the envelope expands, the helium star' s carbon core contracts significantly, the central density and temperature increase rapidly, quickly triggering central carbon ignition. Under the combined action of central carbon burning and shell helium burning, the star expands further, rapidly filling its Roche lobe and initiating Roche lobe overflow. Large amounts of material flow to the neutron star and leave the system from near the neutron star, carrying away substantial angular momentum and reducing the orbital separation. The mass loss process disrupts the star' s surface thermodynamic equilibrium, making the evolution on the Hertzsprung-Russell diagram and the internal temperature-density evolution complex in order to maintain hydrostatic equilibrium and compensate for envelope mass loss.

Furthermore, Figure 5 shows that after silicon core formation, the helium star' s central temperature and density increase again, clearly exceeding the conditions for silicon burning ignition, forming the aforementioned iron and neutron-rich cores in the center. It can be expected that in subsequent evolution, the masses of the iron and neutron-rich cores will further increase.

Figure 6 [Figure 6: see original paper] shows the distribution of some important elements in the helium star' s interior at the end of the numerical simulation, with the horizontal axis representing mass coordinates from the stellar center outward. Only isotopes with mass fractions exceeding 0.1 in any shell are shown. The corresponding isotopes are labeled with text of the same color as the curves. The four solid lines at the left end of the figure (blue, red, green, black) show that four isotopes of iron and chromium dominate in the core region within $0.086M_\odot$, consistent with the previously mentioned iron core mass. The green dotted and red dashed lines show that the mass fractions of ^{16}O and ^{12}C begin to fall below ^{4}He at $M \simeq 1.431M_\odot$. Therefore, the carbon-oxygen core mass is $M_{\rm CO} \simeq 1.431M_\odot$. Additionally, ^{12}C (represented by the red dotted line) never dominates in any shell at any mass coordinate. Therefore, if we define the corresponding core mass using the mass coordinate of the outermost shell where the element dominates (similar to silicon and iron cores), the carbon core mass would become zero at the end of evolution. Clearly, this is similar to the fluctuation in silicon core mass before its maximum and the work of Jiang et al. [**?**], representing a definitional issue rather than an evolutionary outcome.

Limited by numerical simulation constraints, we did not simulate the subsequent evolution process. However, the appearance of silicon, iron, and neutron-rich cores already rules out the possibility of electron-capture supernova triggered by oxygen-neon-magnesium core electron-capture reactions, while the central temperature-density exceeding the silicon burning line ensures that in subsequent evolution, the iron core mass will increase until iron-core collapse supernova occurs, producing a neutron star. Without a hydrogen envelope and with a helium shell mass (about $0.123M_\odot$) exceeding the limit for detection in optical or infrared spectra (about $0.06M_\odot$) [?, ?], the supernova would likely be observed as a Type Ib supernova.

The baryonic mass ($M_{\mathrm{NS}}^{\mathrm{bary}}$) and gravitational mass ($M_{\mathrm{NS}}^{\mathrm{grav}}$) of a neutron star satisfy the following relation [?, ?]:

$$M_{\mathrm{NS}}^{\mathrm{bary}} = M_{\mathrm{NS}}^{\mathrm{grav}} + kM_\odot \left(\frac{M_{\mathrm{NS}}^{\mathrm{grav}}}{M_\odot}\right)^2$$

where the constant coefficient k in the last term reflects the strength of gravitational binding energy; larger k indicates stronger gravitational binding energy, and vice versa. Obviously, the k value is related to the equation of state describing neutron star matter. For a given baryonic mass, a larger constant leads to a smaller neutron star gravitational mass, while a smaller constant leads to a larger gravitational mass. In the literature, following the recommendation of Lattimer and collaborators [?, ?], $k = 0.084$ is typically adopted. Therefore, the initial helium star mass of $2.8M_\odot$ in this work is already very close to the lower limit of the initial helium star mass for the companion in the J1846 system.

4.1 Impact of Supernova Explosion on the Binary Orbit

According to Hills' study [?], the ratio of orbital semi-major axes before and after supernova explosion is [?, ?]:

$$\frac{a_{\mathrm{f}}}{a_{\mathrm{i}}} = \frac{M_{\mathrm{NS,1}} + M_{\mathrm{He,f}}}{M_{\mathrm{NS,1}} + M_{\mathrm{NS,2}}} \left(1 - \frac{2a_{\mathrm{i}}}{GM_{\mathrm{tot}}} V_0 V_{\mathrm{K}} \cos\theta + \frac{a_{\mathrm{i}}}{GM_{\mathrm{tot}}} V_{\mathrm{K}}^2\right)$$

where $M_{\mathrm{He,f}}$ is the helium star mass before explosion, V_{K} and V_0 are the kick velocity of the newly formed neutron star and the pre-explosion orbital velocity of the helium star, respectively, and θ is the angle between them. Assuming the kick' s azimuthal angle relative to the orbital plane before explosion is ϕ, the post-explosion orbital eccentricity satisfies:

$$1-e^2 = \frac{M_{\mathrm{NS,1}} + M_{\mathrm{He,f}}}{M_{\mathrm{NS,1}} + M_{\mathrm{NS,2}}} \left(1 - \frac{2a_{\mathrm{i}}}{GM_{\mathrm{tot}}} V_0 V_{\mathrm{K}} \cos\theta + \frac{a_{\mathrm{i}}}{GM_{\mathrm{tot}}} V_{\mathrm{K}}^2\right) \times (\cos^2\theta + \sin^2\theta \sin^2\phi) + \frac{2a_{\mathrm{i}}}{GM_{\mathrm{tot}}} V_0 V_{\mathrm{K}} \cos\theta - \frac{a_{\mathrm{i}}}{GM_{\mathrm{t}}}$$

Based on binary evolution results, we set the pre-explosion orbital period as $P_{\mathrm{orb}} = 0.53$ d and helium star mass as $M_{\mathrm{He,f}} = 1.554M_\odot$. We adopt the millisecond pulsar mass as its upper limit, $M_{\mathrm{NS,1}} = 1.3455M_\odot$, and simulate the orbital period and eccentricity changes caused by the explosion under isotropically distributed kick velocities. In Figure 7 [Figure 7: see original paper], blue, red, and green data points represent the distributions of post-supernova orbital period and eccentricity for three different kick velocities ($V_K = 100$, 80, 50 km s^{-1}); the black filled circle marks the observational data for J1846. The results show that when $V_K > 80$ km s^{-1}, the system can produce the observed system. If the kick velocity during the explosion is considered small, a shorter pre-explosion orbital period would be needed to produce the observed system.

For our resulting helium star, assuming that all baryonic material within the carbon-oxygen core produces a new neutron star during the supernova explosion, while the helium shell material (about $0.123M_\odot$) is ejected to become supernova remnant material, i.e., $M_{\rm NS}^{\rm bary} = M_{\rm CO} \simeq 1.431M_\odot$. When $k = 0.084$, we obtain the gravitational mass of the newly formed neutron star: $M_{\rm NS,2} \simeq 1.291M_\odot$. Considering equation of state effects, the k value may deviate from 0.084; for example, with $k = 0.1$, we obtain $M_{\rm NS,2} \simeq 1.27M_\odot$, while with $k = 0.07$, we obtain $M_{\rm NS,2} \simeq 1.31M_\odot$.

In fact, observations show that Type Ib supernova explosions eject not only the outermost helium but also other heavier inner elements such as carbon, oxygen, neon, magnesium, silicon, sulfur, etc. [?]. Even if only about $0.008M_\odot$ of inner material is ejected, making the total ejecta mass only about $0.131M_\odot$, the gravitational mass of the second neutron star would drop below about $1.2845M_\odot$ (the observed mass lower limit) when $k = 0.084$.

4.2 System Merger Probability

Double neutron star systems with small orbital periods (below 1 d) are likely to merge within a Hubble time (13.8 Gyr) and be detected as high-frequency gravitational wave sources by ground-based detectors such as LIGO (Laser Interferometer Gravitational-Wave Observatory) and Virgo. For example, the progenitor of gravitational wave signal GW170817, which triggered the first multi-messenger observation, was a double neutron star system [?]. For a double neutron star system with initial semi-major axis a_0 and eccentricity e_0, if orbital energy is lost only through gravitational wave radiation, its merger time can be calculated by [?]:

$$\tau_{\rm GWR} = \frac{304G^3 M_{\rm NS,1} M_{\rm NS,2}(M_{\rm NS,1} + M_{\rm NS,2})}{c^5 a_0^3} \times f(e)$$

where C_1 is a constant depending only on initial eccentricity:

$$C_1 = \frac{(1-e_0^2)^{12/19}}{e_0^{12/19}} \left[1 + \frac{121}{304} e_0^2\right]^{-870/2299}$$

and $f(e)$ is an integral function of eccentricity that, except for the special case $e_0 = 0$, cannot be calculated analytically and must be solved numerically:

$$f(e) = \int_0^{e_0} \frac{e^{29/19}[1 + (121/304)e^2]^{1181/2299}}{(1 - e^2)^{3/2}} de$$

For the observed J1846, when the two neutron star masses are at their observed upper and lower limits, the merger time is about 8.7 Gyr. For the system obtained in this simulation, considering the newly formed neutron star mass at its observed lower limit and the millisecond pulsar mass at its upper limit, with isotropically distributed kick directions, we calculated the merger probability within a Hubble time for different kick velocities. The results are shown in Figure 9 [Figure 9: see original paper]. When the kick velocity is less than 300 km s^{-1}, the system' s merger probability within a Hubble time exceeds 40%, and when the kick velocity is less than 100 km s^{-1}, the merger probability exceeds 50%.

Considering that the supernova explosion process may eject material inside the helium shell (or that constant k takes larger values) as mentioned earlier, we also simulated cases where the second neutron star mass is slightly below its observational lower limit, $M_{\text{NS},2} = 1.28 M_\odot$ (with corresponding millisecond pulsar mass $M_{\text{NS},1} = 1.35 M_\odot$). We also considered the case where constant k takes a smaller value–$k = 0.07$–and only the helium shell is ejected, with the second neutron star mass $M_{\text{NS},2} = 1.31 M_\odot$ and corresponding millisecond pulsar mass $M_{\text{NS},1} = 1.32 M_\odot$. Figure 8 [Figure 8: see original paper] shows the distribution of post-supernova orbital period and eccentricity for these two cases with kick velocity $V_\text{K} = 80$ km s^{-1}. Red data points represent the case with $M_{\text{NS},1} = 1.32 M_\odot$, $M_{\text{NS},2} = 1.31 M_\odot$, while blue data points represent $M_{\text{NS},1} = 1.35 M_\odot$, $M_{\text{NS},2} = 1.28 M_\odot$. The results show that in these two extreme cases, the distributions of post-supernova orbital period and eccentricity are basically consistent. This is because, in equations (7) and (8), the masses of the two components act as a combined quantity. In the simulations of the two cases above, the post-supernova total binary mass was set to the observed mass, which is constant, while the pre-explosion total binary mass difference is small, only $0.04 M_\odot$, and can basically be neglected.

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5 Summary

As one of three double neutron star candidate systems discovered by China' s FAST radio telescope, J1846' s observational data provide precise measurements of orbital period, orbital eccentricity, total binary mass, pulsar mass upper limit, and companion mass lower limit, offering important reference points for testing binary and stellar evolution theory. This paper uses the MESA binary module to simulate the evolution of neutron star-helium star binary systems, attempting to investigate the system' s formation and progenitor evolution. Simulation results show that a binary system composed of a $1.345 M_\odot$ neutron star and a $2.8 M_\odot$ helium star with an initial orbital period of 0.5 d evolves to a final orbital period of 0.53 d. The helium star ultimately develops silicon, iron, and neutron-rich cores, with a carbon-oxygen core mass of $1.431M_\odot$ and a total mass of $1.554M_\odot$. Based on the composition at the evolution endpoint, we can determine that this helium star will undergo an iron-core collapse supernova, producing a neutron star. With the gravitational energy constant $k = 0.084$ [**?**, **?**], even if the ejecta mass from the supernova explosion is only $0.132M_\odot$, the gravitational mass of the newly formed neutron star would be below the observed lower limit of $1.2845M_\odot$. Therefore, under the premise of iron-core collapse supernova, the initial helium star mass of the progenitor for the second neutron star in the J1846 system cannot be lower than $2.8M_\odot$. Furthermore, our simulations of orbital changes caused by supernova explosion indicate that this model can evolve into a double neutron star system similar to J1846.

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Note: Figure translations are in progress. See original paper for figures.