

Constraints on the kinetic energy of type-Ic supernova explosion from young PSR J1906+0746 in a double neutron star candidate

Yi-Yan Yang(杨佚沿), Cheng-Min Zhang(张承民), Jian-Wei Zhang(张见微), and De-Hua Wang(王德华)
Citation: Chin. Phys. B, 2021, 30 (**6**): 068703. DOI: 10.1088/1674-1056/abda2c
Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Effective suppression of beta oscillation in Parkinsonian state via a noisy direct delayed feedback control scheme

Hai-Tao Yu(于海涛), Zi-Han Meng(孟紫寒), Chen Liu(刘晨), Jiang Wang(王江), and Jing Liu(刘静)
Chin. Phys. B, 2021, 30 (**3**): 038703. DOI: 10.1088/1674-1056/abd395

Effect of stochastic electromagnetic disturbances on autapse neuronal systems

Liang-Hui Qu(曲良辉), Lin Du(都琳), Zi-Chen Deng(邓子辰), Zi-Lu Cao(曹子露), Hai-Wei Hu(胡海威)
Chin. Phys. B, 2018, 27 (**11**): 118707. DOI: 10.1088/1674-1056/27/11/118707

Performance analysis of LDPC codes on OOK terahertz wireless channels

Chun Liu(刘纯), Chang Wang(王长), Jun-Cheng Cao(曹俊诚)
Chin. Phys. B, 2016, 25 (**2**): 028702. DOI: 10.1088/1674-1056/25/2/028702

Firing dynamics of an autaptic neuron

Wang Heng-Tong, Chen Yong
Chin. Phys. B, 2015, 24 (**12**): 128709. DOI: 10.1088/1674-1056/24/12/128709

Characterizing neural activities evoked by manual acupuncture through spiking irregularity measures

Xue Ming, Wang Jiang, Deng Bin, Wei Xi-Le, Yu Hai-Tao, Chen Ying-Yuan
Chin. Phys. B, 2013, 22 (**9**): 098703. DOI: 10.1088/1674-1056/22/9/098703

Constraints on the kinetic energy of type-Ic supernova explosion from young PSR J1906 + 0746 in a double neutron star candidate*

Yi-Yan Yang(杨佚沿)[1,†], Cheng-Min Zhang(张承民)[2,‡], Jian-Wei Zhang(张见微)[3], and De-Hua Wang (王德华)[4]

[1] *School of Physics and Electronic Sciences, Guizhou Education University, Guiyang* 550018, *China*
[2] *CAS Key Laboratory of FAST, National Astronomical Observatories, Chinese Academy of Sciences (CAS), Beijing* 100012, *China*
[3] *Astronomy Department, Beijing Normal University, Beijing* 100875, *China*
[4] *School of Physics and Electronic Sciences, Guizhou Normal University, Guiyang* 550001, *China*

(Received 18 June 2020; revised manuscript received 14 December 2020; accepted manuscript online 11 January 2021)

So far among the nineteen pairs of detected double neutron star (DNS) systems, it is a usual fact that the first-born recycled pulsar is detected, however the youngest DNS system PSR J1906+0746, with the characteristic age of 113 kyr, is one of the three detected DNS as a non-recycled and second-born NS, which is believed to be formed by an electron capture or a low energy ultra-stripped iron core-collapse supernova (SN) explosion. The SN remnant around PSR J1906+0746 is too dim to be observed by optical telescopes, then its x-ray flux limit has been given by Chandra. A reference pulsar PSR J1509-5850 with the young characteristic age of 154 kyr was chosen as an object of comparison, which has an SN remnant observed by Chandra and is believed to be formed by iron core SN explosion. We impose a restriction on the maximum kinetic energy of electron-capture (EC) SN explosion that induces the formation of PSR J1906+0746. The estimated result is $(4–8)\times10^{50}$ erg (1 erg$= 10^{-7}$ J), which is consistent with that of the published simulations of the EC process, *i.e.*, a lower value than that of the conventional iron core SN explosion of $(1–2)\times10^{51}$ erg. As suggested, EC process for NS formation is pertained to the subluminous type Ic SN by the helium star with ONeMg core, thus for the first time we derived the kinetic energy of EC SN explosion of DNS, which may be reconciled with the recent observation of type Ic SN 2014ft with kinetic energy of 2×10^{50} erg.

Keywords: neutron star, pulsar, astrophysics, high energy astrophysical phenomena

PACS: 87.19.ly, 87.19.ls, 87.19.lc, 87.16.Vy **DOI:** 10.1088/1674-1056/abda2c

1. Introduction

The PSR J1906+0746, with a highly compact orbit, was discovered by Lorimer *et al.* using the Arecibo L-band Feed-horn Array (ALFA).[1] It is generally assumed to be a double neutron star (DNS) rather than neutron star–white dwarf system, although an alternative possibility is that the first-formed object could be a white dwarf.[2,3] Furthermore, the possibility that such a pulsar could in fact be strange quark stars also cannot be expelled.[4,5] Several studies have been carried out on this candidate DNS since its discovery.[1–3] Due to the companion mass, the substantial eccentricity of the binary orbit, the small spin-down age, the significant spin-down energy loss rate, and the relatively higher magnetic field, it is suggested that the pulsar in this DNS system could be a non-recycled and second-born neutron star (NS).[6] The recycled one should be an unusual pulsar or a potential candidate for another new double pulsar system.

The short-period orbit of DNS makes it valuable to allow exquisite tests of Einstein's theory of general relativity and its prediction of the gravitational waves.[7] In addition, the coalescence of DNSs has been detected as the gravitational-wave (GW) source by LIGO.[8] It was suggested that the galactic birthrate of binaries similar to PSR J1906+0746 is about 60 Myr^{-1} in the context of a simple calculation, which implies that PSR J1906+0746 will play an important role for predicting the inspiral rates of compact binary systems.[1,9] Because of its high magnetic field ($\sim 10^{12}$ Gs, 1 Gs$= 10^{-4}$ T) and the lowest characteristics age ($\sim$ 113 kyr), PSR J1906+0746 offers unique insights and powerful constraints on our physical understanding of the formation process of compact objects and the path of binary star evolution.

A degenerate ONeMg core is formed for the 8 $M_{\odot}$–10 $M_{\odot}$ star, in which the electron captures on ^{24}Mg and ^{20}Ne trigger the collapse of such a degenerate core.[10] When the ONeMg core mass approaches the Chandrasekhar mass, the core will collapse to a low-mass and -kick NS.[11] This type of supernova (SN) is called an "electron capture SN".[12] It is argued that these low-mass NSs were formed by the electron capture

*Project supported by the National Natural Science Foundation of China (Grant Nos. U1938117, U1731238, 11703003, and 11647114), the International Partnership Program of Chinese Academy of Sciences (Grant No. 114A11KYSB20160008), the National Key Research and Development Program of China (Grant No. 2016YFA0400702), the Guizhou Provincial Science and Technology Foundation (Grant No. [2020]1Y019), and the Project of Guizhou Provincial Education Department (Grant No. [2018]058), the Doctoral Project of Guizhou Education University (Grant No. 2020BS021), and the Key Support Disciplines of Theoretical Physics of Department of Education of Guizhou Province, China (Grant No. ZDXK[2015]38).

†Corresponding author. E-mail: yangyiyan@gznc.edu.cn
‡Corresponding author. E-mail: zhangcm@bao.ac.cn

© 2021 Chinese Physical Society and IOP Publishing Ltd

collapse of the degenerate ONeMg cores of helium stars less massive than about 3.5 $M_{\odot}$.[13] The low eccentricity (0.085) of the orbit of PSR J1906+0746 indicates that the second-born NS received hardly any velocity kick at its birth. In combination with the low mass and higher magnetic field of the second-born NS, it suggests that PSR J1906+0746 originated from an electron-capture collapse of a degenerate ONeMg core.[3] Its energy released during formation should not be higher than 10^{51} erg of the usual SN-type Ic. The discovery of SN 2014ft, a type Ic SN with a fast-evolving light curve, indicates that it has an extremely low ejecta mass ($\approx 0.2\ M_{\odot}$) and low kinetic energy (2×10^{50} erg).[14] We interpret SN 2014ft as evidence for ultra-stripped SN that form NS in compact binary systems.

This manuscript is organized as follows: In Section 2, we will present more arguments for the second-form NS in PSR J1906+0746 on its forming by the electron-capture SN. In Section 3, we will discuss the mass loss during the formation of non-recycled pulsar, and give the energy limit for SN during electron capture. Finally, we will present conclusions and discussions in Section 4.

2. Evidence of electron-capture supernova

Until now, approximately 2700 pulsars have been detected in the ATNF Pulsar Catalogue, readers can refer to the following URL:

(https://www.atnf.csiro.au/research/pulsar/psrcat/).[15]

And, almost 400 supernova remnants (SNR) have been discovered in the Milky Way, but only approximately 100 pulsars are associated with SNRs, readers can refer to the following URL:

(http://www.physics.umanitoba.ca/snr/SNRcat/).[16]

We cross checked all of the SNRs, and no SNR matched the locations of PSR J1906+0746. Our explanation is as follows. The energy of a regular SN explosion is far greater than that of an electron-capture SN, and signs of radio emissions for SN explosions are easier to be detected. However, no x-ray photons have been observed near the J1906+0746 radio position.[4] This also confirmed that there is no SNR around PSR J1906+0746. If PSR J1906+0746 were the product of an SN explosion of massive core, then it would be most likely to produce a detectable SNR born in such a short time ($\sim$ 113 kyr) and a distance from 5 kpc to 10 kpc.

DNSs are not disrupted in the case of two SNs, this places strict limits on the nature of these systems' second SN explosion. By studying the recycling scenario of the double pulsar system,[17] the first-formed NS was spun up by transferring angular momentum from its companion, as a consequence, it will be more rapid rotation, then the second-formed NS, with a slower spin period, formed during the secondary SN explosion involving in electron capture or ultra-stripped type.[18–20] PSR J1906+0746 was originated from a high-mass x-ray binary (HMXB), which has undergone common-envelope phases.[2] The long-time interaction between the common-envelope and companion leads to a circularized orbit, resulting in faster spin-up NS. And the second-born, non-recycled NS detected with small mass, low eccentricity and velocity, higher magnetic field is formed in an electron capture SN explosion.[20]

According to the previous theoretical researches of DNS formation,[17] we briefly describe the evolution process of PSR J1906+0746 in the following. Two main sequence (MS) stars with masses of 8 $M_{\odot}$–12 $M_{\odot}$ evolve as an observable HMXB after the first SN explosion.[20] In this stage, the more massive MS star experiences an SN to form an NS with the high magnetic field of about 10^{12} Gs–10^{13} Gs and spin period of 20 ms, like the initial case of Crab pulsar, and the orbital scale of binary system must be so close to ensure mass transfer. A HMXB system will form a PSR J1906+0746-like DNS system after the second MS star evolves to an NS, while the low-mass MS star (*e.g.*, $\sim 8.8\ M_{\odot}$) expands with Roche-lobe overflow and makes such a system unstable. The Roche-lobe overflow makes the magnetic field of unseen recycled NS (first-born) in PSR J1906+0746 decay two magnitude orders, and its spin period decreases to $\sim$ 10 ms–20 ms.[3] The un-stable mass transfer will result in a common envelope, in which it engulfs the first-born NS, and then it spirals in toward the common envelope. Dynamical friction makes NS spin faster and the companion triggers an ultra-stripped SN, leaving behind an NS with the remaining He core companion.[21] The He star then undergoes an SN, and the binary system eventually survives as a PSR J1906+0746-like system, with a short period recycled pulsar with magnetic field $B \sim 10^{12}$ Gs–10^{13} Gs and spin period $P \sim 20$ ms–50 ms, and a non-recycled pulsar (PSR J1906+0746) with magnetic field of about $\sim 10^{12}$ Gs and spin period of 20 ms–30 ms that evolves to its present value of 144 ms by the magnetic dipole radiation.

The evolutionary trajectory of the magnetic field *versus* spin period of PSR J1906+0746 is shown in Fig. 1. In PSR J1906+0746 binary system, the magnetic field of the first-formed pulsar is likely to occur at $\sim 10^{12}$ Gs at birth. After a period of evolution, the companion star (*e.g.* about 8 $M_{\odot}$–10 $M_{\odot}$) evolves and accretion happens, while the magnetic field of the first born NS decays to $\sim 10^{9}$ Gs by accreting matter of about 0.01 $M_{\odot}$ from the companion. Later on, the companion occurs an electron capture SN, while the second NS is born with the normal magnetic field of $\sim 10^{12}$ Gs. Thus, the DNS system survives with a pair of NSs, a short period recycled pulsar (first born) with magnetic field $\sim 10^{9}$ Gs, and a non-recycled pulsar (second born) with magnetic field of about 10^{12} Gs.[22]

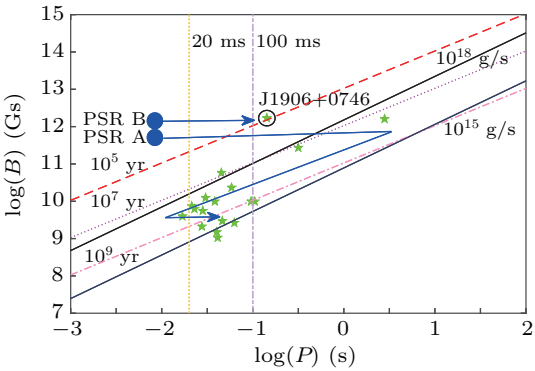


Fig. 1. Diagram of magnetic field *versus* spin period of DNS, where the spin periods of three NSs (J1906+0746, J1755-2550, and 0737-3039B) are greater than 100 ms with the strong magnetic fields of about 10^{12} Gs.[1,23–25] The two blue solid arrow lines represent the general evolutionary trajectories of PSR J1906+0746, where PSR-A (PSR-B) stands for the recycled (non-recycled) NS. Dashed, dotted, and dashed–dot lines represent the characteristic ages of 10^5 yr, 10^7 yr, and 10^9 yr, respectively, and two straight solid lines, from the upper to lower, stand for the spin-up lines with the accretion rates of 10^{18} g/s and 10^{15} g/s.[11]

To prove the concept of the symmetric SN, several theoretical studies and simulations have been carried out, but there is currently no observational evidence to test them.[26] PSR J1906+0746 should have a much smaller kick velocity, which can be supported by the following arguments. Based on observational data, the average velocity of the proper motion for 322 pulsars is about 400(40) km·s^{-1}.[27] Then, for the binary pulsars, their velocities are usually as low as 100 km·s^{-1}.[28] Small eccentric DNS systems are constrained to have low-mass ejections and low-kick velocities ($\lesssim$30 km·s^{-1}), and this strongly suggests that an electron capture type SN as the origin of the companion.[29] Similarly, from theoretical simulation, the second-born NSs, in a low eccentricity ($\leq$0.4) DNS system, should have low kick velocities of about $\lesssim$80 km·s^{-1} through the electron capture SN formation channels.[30] On the other hand, that a DNS binary may have a high kick velocity of up to 1000 km·s^{-1} is merely based on SN simulations,[20] where the dominant reason is the gravitational tug-boat mechanism that results in a high velocity.[31] We therefore estimate its orbital velocity $v \simeq \sqrt{GM/a} \simeq 450$ km·s^{-1}, where G and a are the gravitational constant and orbit scale, respectively, and the escape velocity $v_1 \simeq \sqrt{2GM/a} \simeq 635$ km·s^{-1}. The kick velocity of PSR J1906+0746 should be much less than the above limit in the same direction, otherwise this DNS system will be highly eccentric or break apart.

We adopted a publicly available code dart_board to simulate the kick velocity generated during the SN explosion for PSR J1906+0746, in which the Markov chain Monte Carlo methods were used, readers can refer to the following URL: (https://dart-board.readthedocs.io/en/latest/).[32] We obtained the kick velocity ranging from 5 km/s to 560 km/s at 99% level (also see Fig. 2). This simulation result of PSR J1906+0746

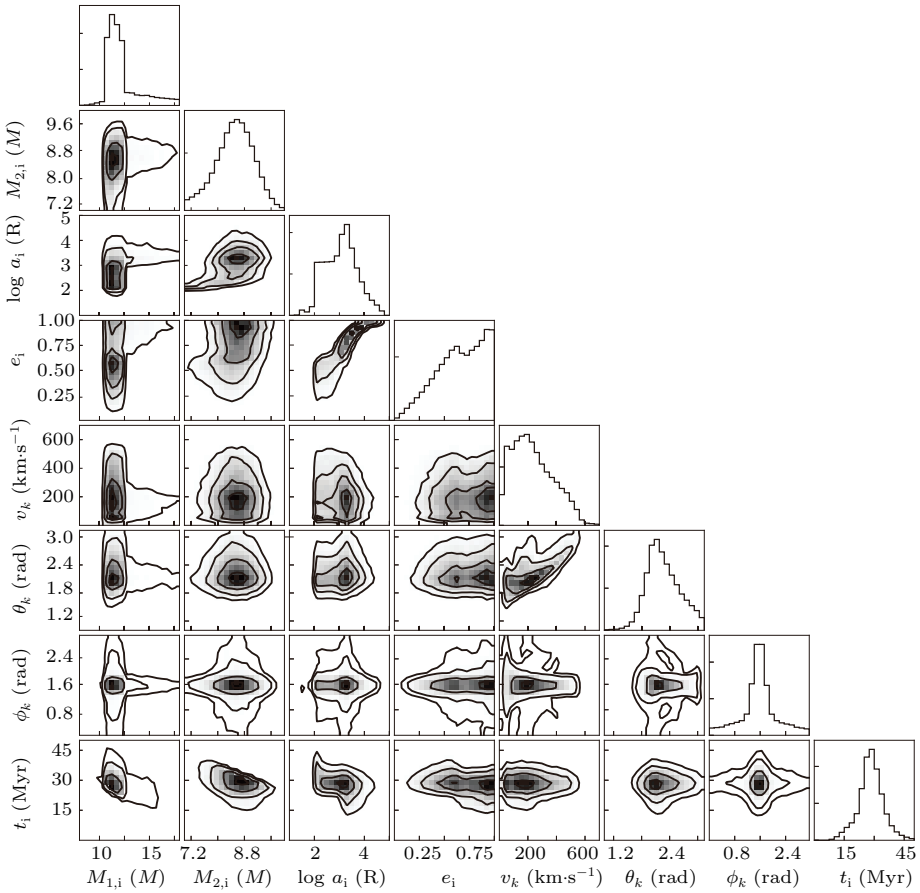


Fig. 2. The one-dimensional (1D) histograms among the eight simulation parameters, involving the binary components initial masses: $M_{1,i}$ and $M_{2,i}$; the initial separation, a_i; the initial eccentricity, e_i; the SN natal kick magnitude v_k, the kick polar and azimuthal angle (θ_k and ϕ_k), and the system age (t_i). The posterior distribution that produces PSR J1906+0746 is obtained by means of the code dart_board. The three input parameters are the primary mass (M_1), the secondary mass (M_2) and the current orbital eccentricity of PSR J1906+0746 on the usage of dart_board.[32]

is consistent with that of previous work, where the kick velocity ranging from 5 km/s and 170 km/s is at 60% level, and from 5 km/s to 510 km/s is at 95% level.[33] Therefore, both simulations indicate that the kick velocity of PSR J1906+0746 has a relatively low value with high confidence level.

3. Energy restriction

3.1. Theoretical calculation of exploding energy

During the formation of DNS, the new-born NS forming at second core collapse determined their final orbital characteristics due to mass loss and SN kick. If SN explosion is symmetric, we can obtain the expression for the pre-supernova mass of helium star (HeS) $M_{\rm c,t}$,[20]

$$M_{\rm c,t} = e(M_{\rm c} + M_{\rm p}) + M_{\rm c}, \tag{1}$$

where e is eccentricity, $M_{\rm p}$ and $M_{\rm c}$ are the masses of the first and second NS's. Taking the data from Table 1, we can obtain the pre-supernova mass of helium star $M_{\rm c,t} = 1.521\ M_{\odot}$. The pre-supernova HeS with low-mass typically form from HeS–NS binaries.[28] This includes the mass range where companion is expected to end their evolution in an electron-capture SN. It is consistent with the predicted model, the masses of the HeS at the electron capture SN explosions are 1.43 $M_{\odot}$–2.37 $M_{\odot}$, with metal (ONeMg) cores of 1.37 $M_{\odot}$–2.15 $M_{\odot}$.[21] The final mass range of NS is widely distributed from 1.2 $M_{\odot}$ to 1.9 $M_{\odot}$. Due to releasing binding energy in electron capture SN process, the NS will decrease its mass by its bind mass $M_{\rm ns}^{\rm bind} = 0.084 \times M_{\rm ns}^2/M_{\odot}$.[34] In the formation the second NS process, the loss of mass ($M_{\rm ej}$) is given by

$$\begin{aligned} M_{\rm ej} &= M_{\rm c,t} - M_{\rm c} - M_{\rm c}^{\rm bind} \\ &= M_{\rm c,t} - M_{\rm c}(1 + 0.084 M_{\rm c}/M_{\odot}). \end{aligned} \tag{2}$$

The loss mass is about 0.09 $M_{\odot}$ for PSR J1906+0746.

New-born NS originated from low-mass SN explosions (including ultra-stripped SN[18]) can be expected to have very small kick velocities, with very thin envelopes around their degenerate ONeMg or low mass iron cores. The SN is expected to release very low energy of the order of 10^{50} erg. The explosion energy and NS baryon mass by performing neutrino radiation hydrodynamics simulations had been calculated, and the results matched well the model parameters from fitting light curves of SN 2005ek[19]. In the process of forming DNS, the mass of companion is about 1.3 $M_{\odot}$, the loss of companion mass = 0.2 $M_{\odot}$, the explosion energy $\sim 5 \times 10^{50}$ erg. One-dimensional simulations of SN explosions from the collapse of ONeMg cores in spherical symmetry for progenitor stars in the 8 $M_{\odot}$–10 $M_{\odot}$ range suggest that such SNs are powered by neutrino heating and by the neutrino-driven wind of the newly formed NS, and this events has a low explosion energy of about 1×10^{50} erg, and this model is tightly related to the subluminous type II-P SN.[29] Two-dimensional (2D) and three-dimensional (3D) explosion simulations of electron capture SN have also been carried out and the explosion energies range from $\sim 3 \times 10^{49}$ erg to $\sim 1.6 \times 10^{50}$ erg.[26] In principle, the electron capture SNs are expected to come from stars with initial mass lying between 8 $M_{\odot}$–10 $M_{\odot}$ which will lead to observation properties of low-luminosity type II-P SN. However, the simulated explosion energy (1×10^{50} erg) of the low-luminosity type II-P SN was slightly lower than the explosion energy of the type Ic SN (2×10^{50} erg) in an electron-capture SN model.[14,26,29]

The kinetic energy of SN and the mass of neutrino-heated post shock ejecta can be approximated by a roughly linear relationship[31]

$$E_{\rm exp} \simeq \varepsilon \beta_{\rm v} M_{\rm ej}, \tag{3}$$

where the parameter ε is considered as a constant, in the order of magnitude of about (5–8)$\times 10^{18}$ erg·g^{-1}.[31] We presume that the value of the total postshock mass as described by the parameter (transfer factor) $\beta_{\rm v}$ is around unit (~ 1). If PSR J1906+0746 experienced the usual SN explosion, then the ejecta mass $M_{\rm ej}$ is around 0.1 $M_{\odot}$, which gives the kinetic energy of this kind SN to be about (1–1.6)$\times 10^{51}$ erg.

3.2. Observational constraints of electron capture supernova exploding energy

Though PSR J1906+0746 is a young pulsar with an age of about 113 thousand years, there is no clear evidence to indicate any trace of its SNR nearby. In other words, for such a young NS system, its SNR should be visible at a distance of about 6 kpc if it is formed by the iron core SN explosion. Thus, no SNR in the low limited flux of x-ray luminosity around PSR J1906+0746 implies that its progenitor should have experienced a low energy electron capture explosion. To evaluate the electron capture explosion energy of the progenitor of young DNS PSR J1906+0746, as a reference, we select another young pulsar PSR J1509-5850 with a similar characteristic age of $\sim$ 154 kyr, which is derived by its spin period and its derivative ($P = 88.9$ ms, $\dot{P} = 0.92 \times 10^{-14}$ s/s).[35] It has a known SNR, and is located in SNR G034.0+20.3 with a distance of about 3.8 kpc, and the observed tail flux of x-ray is 2×10^{-13} erg·s^{-1}·cm^{-2} in 0.5 keV–8 keV band.[36]

A simple relationship between the total energy (E) of the NS progenitor explosion and the emission flux (f) of SNR can be approximately expressed as

$$E \propto f, \tag{4}$$

as inferred from Eq. (18) in the review paper of SN.[37]

For both pulsars J1906+0746 and J1509-5850, their ages and distances are very similar, so we can estimate the ratio Φ

of the two explosion energies by the SNR flux ratio, as described below,

$$\Phi \equiv \frac{f_{1906+0746}}{f_{1509-5850}} \simeq \frac{E_{1906+0746}}{E_{1509-5850}}, \quad (5)$$

where $f_{1906+0746}$ and $E_{1906+0746}$ ($f_{1509+5850}$ and $E_{1509+5850}$) represent the SNR flux and SN explosion energy of J1906+0746 (J1509-5850), respectively.

The measured 0.5 keV–8 keV flux of the feature around J1906+0746 has an upper limit of 3.1×10^{-14} erg·s^{-1}·cm^{-2}.[6] Let us assume that the young pulsar PSR J1509-5850, located in SNR G034.0+20.3, is originated from a massive iron-core collapse SN explosion, with the progenitor stellar mass of about 15 $M_\odot$, the kinetic energy of such a type II iron-core SN explosion is approximately (1–2)$\times10^{51}$ erg. According to Eq. (4), we can conclude that the upper limit of the electron-capture SN explosion energy for J1906+0746 should be (4–8)$\times10^{50}$ erg, which is lower than the usual value for the iron-core SN explosion energy of (1–2)$\times10^{51}$ erg.[38]

Theoretically, we obtained the kinetic energy of J1906+0746 undergone the usual SN explosion to be about (1–1.6)$\times10^{51}$ erg, under the assumption that transfer factor $\beta_{\rm v}$ is around 1 and the ejecta mass $M_{\rm ej}$ is around 0.1 $M_\odot$. Observationally, we estimated the upper limit of the kinetic energy of the electron-capture SN explosion for PSR J1906+0746, found that this energy value is about (4–8)$\times10^{50}$ erg by comparing with PSR J1509-5850. According to Eq. (3) ($E_{\rm exp}\simeq\varepsilon\beta_{\rm v}M_{\rm ej}$), we are taking the lower limiting value of the $E_{\rm exp}\sim4\times10^{50}$ erg, and the upper limit value of $\varepsilon\sim8\times10^{18}$ erg$\cdot$g^{-1}. In the process of forming PSR J1906+0746, in fact, we calculated that the magnitude of parameter β_v is about 0.25. This will result in the energy of the electron-capture SN explosion to be around (2.5–4)$\times10^{50}$ erg. Therefore, we also put a rough constraint on the transfer factor $\beta_{\rm v}$ for this kind of SN explosion.

4. Conclusion and discussion

In this work, based on the x-ray flux limit, we presented that the young pulsar PSR J1906+0746 in DNS candidate system has experienced the electron-capture process of ultra-stripped SN explosion, classified as the type-Ic SN. The estimated upper limit of its SN kinetic energy is consistent with the recent observation of type-Ic SN 2014ft with the kinetic energy of 2×10^{50} erg, which is much less than that of the conventional Type-II iron-core SN of (1–2)$\times10^{51}$ erg. Our result has presented a meaningful constraint on various simulations and models about the electron-capture SN explosion. As the neutrino-driven mechanism accounts for the electron-capture SN, the total mass of the neutrino heated ejecta determines the energy of the explosion.

Since PSR J1906+0746 is such a young pulsar at a distance of about 6 kpc, its SNR should be observable by optical telescope if it experienced iron-core SN explosion. However, its SNR has not yet been detected until now. One possibility is that the low energy type-Ic SN is attributed to the formation of PSR J1906+0746, which is termed as "ultra-faint" SN as recently observed.[14]

Because PSR J1906+0746 is located very close to the galactic plane, the gas and dust around this region are likely to absorb the x-rays emitted. The absorption of x-rays by hydrogen gas has been considered, and the hydrogen column density is obtained as about $n_{\rm H}=0.7\times10^{22}$ cm^{-2} by fitting an absorbed power-law model.[6] The x-ray emissions from the pulsar or its companion had not been detected, the reasons of which may be either the very high absorption or the x-ray pulse beams of PSR J1906+0746 do not sweep across the earth. However, a puzzling extended structure like a tilted ring around the pulsar has been tentatively detected.[6] The ring-like structure would be the unusual declaimed tentative pulsar wind nebula around an under-luminous PSR J1906+0746, most likely, as an indication of the remnant by a symmetric electron-capture SN.

References

[1] Lorimer D R, Stairs I H, Freire P C, Cordes J M, Camilo F, Faulkner A J, Lyne A G, Nice D J, Ransom S M, Arzoumanian Z, Manchester R N, Champion D J, van Leeuwen J , Mclaughlin M A, Ramachandran R, Hessels J W, Vlemmings W, Deshpande A A, Bhat N D, Chatterjee S, Han J L, Gaensler B M, Kasian L, Deneva J S, Reid B, Lazio T J, Kaspi V M, Crawford F, Lommen A N, Backer D C, Kramer M, Stappers B W, Hobbs G B, Possenti A, D'Amico N and Burgay M 2006 *ApJ* **640** 428

[2] van Leeuwen J, Kasian L, Stairs I H, Lorimer D R , Camilo F, Chatterjee S, Cognard I, Desvignes G, Freire P C C, Janssen G H, Kramer M, Lyne A G, Nice D J, Ransom S M, Stappers B W and Weisberg J M 2015 *ApJ* **798** 118

[3] Yang Y Y, Zhang C M, Li D, Wang D H, Pan Y Y, Lingfu R F and Zhou Z W 2017 *ApJ* **835** 185

[4] Huang Y F and Yu Y B 2017 *ApJ* **848** 115

[5] Kuerban A, Geng J J, Huang Y F, Zong H S and Gong H 2020 *ApJ* **890** 41

[6] Kargaltsev O and Pavlov G G 2009 *ApJ* **702** 433

[7] Kramer M and Stairs I H Freire 2008 *Ann. Rev. Astron. Astrophys.* **46** 541

[8] Abbott B P, Abbott R, Abbott T D, *et al.* 2017 *Phys. Rev. Lett.* **119** 161101

[9] Pol N, McLaughlin M and Lorimer D R 2019 *ApJ* **870** 71

[10] Suzuki T, Toki H and Nomoto K. 2016 *ApJ* **817** 163

[11] van den Heuvel E P J 2017 *JApA* **38** 45

[12] Nomoto K 1984 *ApJ* **277** 791

[13] Dewi J D M, Podsiadlowski P and Sena A 2006 *MNRAS* **368** 1742

[14] De K, Kasliwal M M, Ofek E O, Moriya T J, Burke J, Cao Y, Cenko S B, Doran G B, Duggan G E, Fender R P, Fransson C, Gal-Yam A, Horesh A, Kulkarni S R, Laher R R, Lunnan R, Manulis I, Masci F, Mazzali P A, Nugent P E, Perley D A, Petrushevska T, Piro A L, Rumsey C, Sollerman J , Sullivan M and Taddia F 2018 *Science* **362** 201

[15] Manchester R N, Hobbs G B, Teoh A and Hobbs M 2005 *AJ* **129** 1993

[16] Ferrand G and Safi-Harb S 2012 *Advances in Space Research* **49** 1313

[17] Bhattacharya D and van den Heuvel E. P J 1991 *Phys. Rep.* **203** 1

[18] Tauris T M, Langer N, Moriya T J, Podsiadlowski P, Yoon S C and Blinnikov S I 2013 *ApJL* **778** L23

[19] Tauris T M, Langer N and Podsiadlowski P 2015 *MNRAS* **451** 2123

[20] Tauris T M, Kramer M, Freire P C C, Wex N, Janka H T, Langer N, Podsiadlowski P, Bozzo E, Chaty S, Kruckow M U, van den Heuvel E P J, Antoniadis J, Breton R P and Champion D J 2017 *ApJ* **846** 170
[21] Dewi J D M, Podsiadlowski P and Pols O R 2005 *MNRAS* **363** L71
[22] Zhang C. M and Kojima Y. 2006 *MNRAS* **366** 137
[23] Ng C, Kruckow M U, Tauris T M, Lyne A G, Freire P C C, Ridolfi A, Caiazzo I, Heyl J, Kramer M, Cameron A D, Champion D J and Stappers B 2018 *MNRAS* **476** 4315
[24] Burgay M, D'Amico N, Krame M, *et al.* 2003 *Science* **426** 531
[25] Lyne A G, Burgay M, Kramer M, Possenti A, Manchester RN, Camilo F, McLaughlin M A, Lorimer D R, D'Amico N, Joshi B C, Reynolds J and Freire P C C 2004 *Science* **303** 1153
[26] Gessner A and Janka H T 2018 *ApJ* **865** 61
[27] Hobbs G, Lorimer D R, Lyne A G and Kramer M 2005 *MNRAS* **360** 974
[28] Podsiadlowski Ph, Dewi J D M, Lesaffre P, Miller J C, Newton W G and Stone J R 2005 *MNRAS* **361** 1243
[29] Beniamini P and Piran T 2016 *Mon. Not. R. Astron. Soc.* **456** 4089
[30] Shao Y and Li X D 2018 *ApJ* **867** 124
[31] Janka H T 2017 *ApJ* **837** 84
[32] Andrews J J, Zezas A and Fragos T 2018 *ApJS* **237** 1
[33] Wong T W, Willems B and Kalogera V 2010 *ApJ* **721** 1689
[34] Lattimer J M and Yahil A 1989 *ApJ* **340** 426
[35] Kargaltsev O, Pavlov G G, Klingler N and Rangelov B 2017 *J. Plasma Phys.* **83** 635830501
[36] Klingler N, Kargaltsev O, Rangelov B, Pavlov G G, Posselt B and Ng C Y 2016 *ApJ* **828** 70
[37] Chevalier R A 1977 *ApJ* **213** 52
[38] Woosley S and Janka T 2005 *Nat. Phys.* **1** 147