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Constraints on Estimation of Radius of Double Pulsar PSR J0737-3039A and Its Neutron Star Nuclear Matter Composition *

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The aspect of formation and evolution of the recycled pulsar (PSR J0737-3039 A/B) is investigated, taking into account the contributions of accretion rate, radius and spin-evolution diagram (B–P diagram) in the double pulsar system. Accepting the spin-down age as a rough estimate (or often an upper limit) of the true age of the neutron star, we also impose the restrictions on the radius of this system. We calculate the radius of the recycled pulsar PSR J0737-3039 A ranges approximately from 8.14 to 25.74 km, and the composition of its neutron star nuclear matters is discussed in the mass-radius diagram.

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PSR J0737-3039 A/B[1,2] is the only known double neutron star (DNS) system in which both neutron stars (NSs) have been detected as pulsars, allowing studies on plasma physics, general relativity and matter in the strong-field regime.[3,4] Additionally, providing new insights into the evolution of DNS systems and for improving models of such matter are valuable guidance.[5,6] The first-born, recycled pulsar of the system, PSR J0737-3039A (hereafter pulsar A), has a spin period of 22.7 ms. The second-born and slower PSR J0737-3039B (hereafter pulsar B) rotates every 2.8 s. The two pulsars orbit each other in a tight (Porb≅2.4 hrs) and moderately eccentric ($e \cong 0.088$) orbit.

The radius of DNS has been shown to probe the ultra-dense matter equation of state (EOS). It is connected to the matter composition and outcomes of supernova explosions.[7] Neutron star radius measurement has progressed significantly in the past decade and a number of different techniques have been employed.[8] Most methods that are currently used rely on the detection of thermal emission from the surface of the star, either to measure its apparent angular size or to detect the effects of the NS space-time on this emission to extract the radius information. However, the methods of measuring NS radius mainly contain spectroscopic and timing techniques, these rely on breaking the degeneracies between the mass and radius introduced by general relativistic effects. The precise and reliable measurements of the radius of NS would provide valuable guidance for improving models for describing properties of cold matter with densities above the saturation density of nuclear matter.

In this Letter, we analyze the evolutionary path, calculate and restrain the radius of PSR A in double pulsar J0737-3039 A/B, respectively. We propose that PSR B is the secondly formed non-recycled possibly involving electron-capture onto an O-Ne-Mg core. The evolutionary track of double J0737-3039 is described. Furthermore, we discuss the properties of magnetic field and characteristic age for J0737-3039 A/B. The possible nuclear matter composition of PSR A is also discussed.

It is generally thought that DNS systems result from one of two evolutionary scenarios, which we briefly describe here. (1) Electron-capture supernovae: here an O-Ne-Mg core passes a threshold density that allows electrons to be captured on ^{24}Mg, separates itself in how the secondary star evolves to form an NS. This decreases the electron degeneracy pressure, which in turn lowers the Chandrasekhar mass of the core, inducing its collapse.[6,9,10] This would result in low NS velocities, since this type of event is thought to proceed over a much shorter timescale than that needed to develop the instabilities thought to cause substantial SNe kicks and has also been invoked to explain the formation of a subset of NSs with significantly lower measured masses relative to the overall known. This would result in low NS velocities. (2) Core collapse supernovae: Bhattacharya and Heuvel[11] think that two NSs are formed from massive binary system (∼8–25 $M_\odot$), where the more massive star initially undergoes a supernova explosion to form a first NS by stably transferring matter to the

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secondary star, before second collapsing to explode in a supernova, leaving behind the first-formed NS in a high-mass x-ray binary (HMXB).[12] The spin period of the NS decays with the magnetic dipole emission, while the secondary less massive star evolves. During the evolution of the secondary, as un-stable mass transfer, the common envelope (CE) is formed and engulfed the first born NS, and it accretes matter from the accretion disk and acquires the angular momentum that spins it up to the short period.[13] Dynamical friction results in the ejection of the CE, leaving behind a short-period recycled pulsar and a 'normal' pulsar.

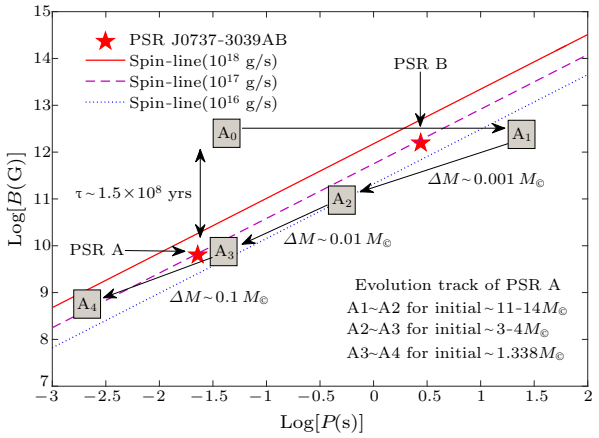

Fig. 1. The evolution track of recycled pulsar J0739-3039 A along the B–P diagram.

PSR J0737-3039 A/B is pointed to a different evolutionary scenario compared with most other known DNS systems. Here we mainly discuss the evolutionary track of the PSR A. As the shortest spin period (22 ms), shortest orbital period (0.102 d) and lowest eccentricity (0.088), the possible evolution of double pulsar J0737-3039 may undergo 5 stages as shown in Fig. 1.

A0: At the very beginning of the binary evolution, the two main sequence stars start to evolve, the more massive (primary) one (e.g., 10–14 $M_\odot$), evolves off and experiences an SNe explosion to form an NS, whose birth position in the B–P diagram lies in the region A0 with the high magnetic field of about 10^{12}–10^{13} G and spin period of tens of milliseconds (like the crab pulsar $B \sim 10^{12}$ G, $P \sim 30$ ms).

A0–A1: The first born pulsar starts to evolve from A0 to A1, on account of the electromagnetism emission while the magnetic field is unchanged. If the companion mass is massive enough (e.g., $\geq 10\,M_\odot$), with sufficiently long age of the main sequence (e.g., $\sim 10^7$ yr), the pulsar can arrive at the position A1 ($B \sim 10^{12}$ G and $P >\sim 10$ s), where the NS cannot be seen as a pulsar.

A1–A2: The dead pulsar can be spun-up by the accretion and recycled from A1 to A2 with the condition that its companion leaves its main sequence to the red giant. The stellar wind accretion and/or Roche-lobe overflow makes the pulsar magnetic field decay one magnitude order and spin decrease to ~ 1 s. The evolution will stop at the spin-up line where the stellar spin equals the orbital Keplerian frequency of the magnetosphere-disk, which is related to the different accretion rates. The NS evolution will continue following A1–A2 along the spin-up line, until the NS accretes about 0.001–0.01 $M_\odot$.

A2–A3: The companion decreases the electron degeneracy pressure, which in turn lowers the Chandrasekhar mass of the core, inducing an electron capture supernova, the binary system survives with a pair of NSs, a short period recycled pulsar with magnetic field $B \sim 10^9$–10^{10} G and spin period $P \sim 20$–100 ms, and a non-recycled pulsar, with magnetic field of about 10^{12}–10^{13} G and spin period of more than 10 ms.

A3–A4: Due to the electromagnetism emission, the period and magnetic field of the PSR A might go on decaying until it is a normal pulsar.

It has been assumed that the loss of rotation energy of the pulsar equals the amount of magnetic dipole radiation. The spin period (P_s) and the spin-down rate ($\dot{P}$) of a pulsar can be combined to yield an estimate of the average strength of the dipole component of the magnetic field at its surface and characteristic age[11,14]

$$\begin{aligned} B &= \Big(\frac{3c^3 I}{8\pi^2 R^6} P\dot{P}\Big)^{1/2} \\ &= 9.06\times10^{11}(G)\times P^{1/2}\Big(\frac{M}{M_\odot}\Big)^{1/2} \\ &\quad\cdot\Big(\frac{\dot{P}}{10^{-15}}\Big)^{1/2}\Big(\frac{R}{10\,\mathrm{km}}\Big)^{-2}, \end{aligned} \tag{1}$$

where I is the moment of inertia and is expressed as $\frac{2}{5}MR^2$ (gcm^2) for a homogeneous stellar density, R is the stellar radius, and M is the NS mass.

In the standard accretion spin-up model, the spin-up will end when the NS reaches its so-called 'equilibrium' spin period $P_{\rm eq}$,[15]

$$P_{\rm eq} = 3.1\,(\mathrm{ms})B_9^{6/7}\Big(\frac{M}{M_\odot}\Big)^{-5/7}\Big(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\Big)^{-3/7}R_6^{18/7}, \tag{2}$$

where B_9 is the dipole magnetic field in units of 10^9 G. Spin period $P_{\rm eq}$ is more influenced by the accretion rate $\dot{M}$ (varied in about 2–3 magnitude orders), and less affected by the stellar mass and radius. The mass of NS among DNS ranges from 1 $M_\odot$ to 2 $M_\odot$, and radius may be from 10 km to 20 km.[16,17]

Assuming certain models for the spin evolution of both pulsars due to steady or evolving braking torques, we can therefore use the spin-down rates observed to constrain the ages of the pulsars,

$$t = \frac{P}{(n-1)\dot{P}}\Big[1-\Big(\frac{P_0}{P}\Big)^{n-1}\Big], \tag{3}$$

where P_0 is the initial spin period, and n (defined as $\dot{P}\propto P^{2-n}$) is the braking index. For a normal pulsar,

we assume ($P_0 \ll P$) and $n = 3$, the real age of a pulsar can then be conveniently approximated by its characteristic age τ,[2,14,18]

$$t = \tau \equiv \frac{P}{2\dot{P}}, \quad \text{for } P_0 \ll P, \ n = 3. \tag{4}$$

According to the pulsar recycling scenario, the PSR A is identified as the first-born NS which was spun up (recycled) to the 'equilibrium period' by the mass accretion from the progenitor of PSR B. The PSR B is then the normal NS formed during the ECS of the secondary.[6] The age of the normal pulsar (PSR B) can be conveniently approximated by its characteristic age, since its present spin period is much longer than the usual spin period at birth,

$$t_{\rm sd,B} \simeq \tau_{\rm B} \equiv \frac{P}{2\dot{P}}, \quad \text{for } P_0 \ll P, \ n = 3. \tag{5}$$

By following the work of Lorimer *et al.*,[14] we assume that the spin-down age for PSR A ($t_{\rm sd,A}$) can refer to the time since its spin-up ceased, and should be equal to the time since PSR B was birthed as an NS. We therefore assume

$$t_{\rm sd,A} = t_{\rm sd,B}. \tag{6}$$

According to Eq. (3), we find

$$t_{\rm sd,A} = \tau_{\rm A}\left[1 - \left(\frac{P_{\rm eq}}{P_{\rm A}}\right)^2\right], \quad \text{for } n = 3, \tag{7}$$

where $\tau_{\rm A} = P_{\rm A}/2\dot{P}_{\rm A}$ is the characteristic age of the recycled pulsar PSR A, and $P_{\rm eq} = 19.78\,$ms is obtained. Combination of Eqs. (1) and (2) yields

$$R = 0.98\,({\rm km})\left(\frac{M}{M_\odot}\right)^{1/3}\left(\frac{\dot{P}_{\rm A}}{10^{-15}ss^{-1}}\right)^{-1/2} \cdot \left(\frac{\dot{M}}{10^{18}gs^{-1}}\right)^{1/2}, \tag{8}$$

where the parameters $M_{\rm A} = 1.338\,M_\odot$, $\dot{P}_{\rm A} = 1.76 \times 10^{-18}ss^{-1}$ are adopted, and then we obtain the relation between the radius and the accretion rate (see Fig. 2). The radius of the recycled PSR A $R \simeq 8.14\,$km ($R \simeq 25.74\,$km) for the accretion rate $\dot{M}_{\rm A} = 0.1\dot{M}_{\rm Edd}$ ($\dot{M}_{\rm A} = \dot{M}_{\rm Edd}$).[19]

The internal structure of NS is not exactly known because of uncertainties in the matter EOS in NS cores. The NS internal composition might be constructed solely with normal matter (neutrons, protons, electrons, muons), or it may contain kaon condensates, hyperons, pion condensates, or quark matter.

Miller investigated that $1.2\,M_\odot$ is a conservative lower limit for the mass of an NS formed from a supernova.[20] The cores of these tiny, dense stellar leftovers might conceal new states of matter, and the possible compositions for an NS contain strange matter and normal matter, or a Bose–Einstein condensate of pions if their mass is higher than $1.8\,M_\odot$. The recent measurement of the radio pulsar PSR J1614-2230 yielded a mass of $\sim 1.97\,M_\odot$[21] and $\sim 2.01\,M_\odot$ for PSR J0348+043 observed through the Shapiro delay technique, which may give stringent constraints on the EOS of dense matter.[22] Such a high NS mass measurement has raised great interests in the structure and composition of NSs, since it might rule out many predictions of non-nucleonic components in NS interiors. Li *et al.*[23] think that massive NSs require a very stiff EoS and set a strong upper limit on the dark dense matter particle mass.

From the updated measured pulsar masses,[16] information is insufficient to infer the nuclear matter compositions inside the central compact objects. Theoretically, pulsars may consist of hadronic matter only, hadronic and quark matter either bearing or not a mixed phase or quark matter only (see Fig. 3).[24,25]

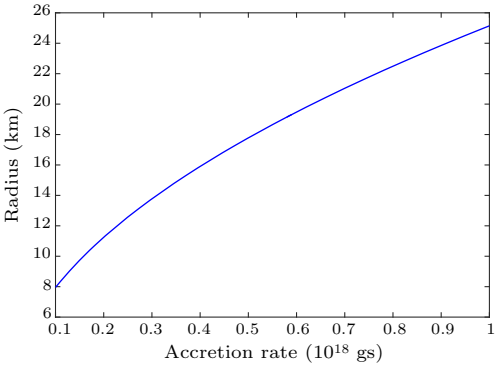

Fig. 2. The relationship between the radius and the accretion rate. The curve line stands for the possible R range of the recycled pulsar of PSR A.

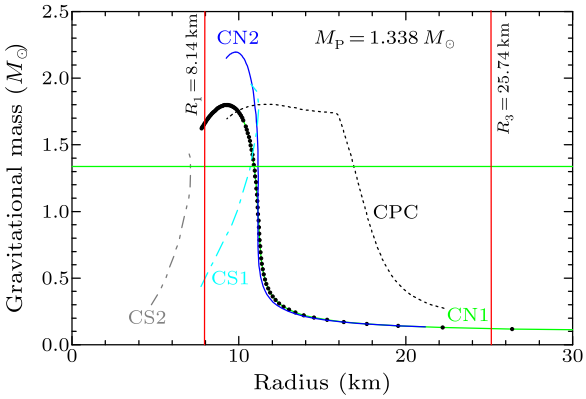

Fig. 3. The evolution track of different scenarios based on the relationship of mass–radius diagram. The theoretical curves of EOSs are plotted:[20] stars containing strange quark matter (CS1 and CS2), stars made of normal neutron matter (CN1 and CN2), and stars with pion condensate cores (PCC), the horizontal line stands for $M_{\rm A} = 1.338\,M_\odot$, and two vertical lines stands for possible R of range the recycled PSR A as 8.14 km and 25.74 km, respectively.

Recycled NSs in binary systems should find that the stiffness increases, and that the phase transition of nuclear matter may occur.[26] Chatziioannou *et al.*[27] claimed that NSs contain only quark matter, by car-

rying out a Bayesian model selection analysis, but hybrid stars containing both normal and quark matter are typically harder to distinguish from normal matter stars (see Fig. 3). The different EOS models proposed in the literature differ in the NS composition they assume, masses around $1.4\,M_\odot$ would provide indications of the existence or absence of strange quark stars, while the presence of kaon condensates or hyperons in NS inner cores cannot be easily confirmed.

The detection of hyperon or kaon condensates in NS interiors requires high mass stars, since it is only at these high masses, and the very highest central densities that these condensates form. Moreover, most NSs are expected to have masses around the nearby $1.4\,M_\odot$, rarely reaching $2\,M_\odot$ required for hyperons and kaons detection. Unlike kaon condensates and hyperons that can only exist in combination with normal matter, quark matter can form both with and without normal matter.

The observed properties of double pulsars reveal much information about the evolutionary history of different types of binaries (including their spin periods, magnetic field, component masses, and supernova processes).[28] From the above discussion, it turns out that the spin-down age of the normal PSR B which is essentially the same as the true age of recycled PSR A. Thus we can constrain the recycled pulsar formation and evolution at equilibrium period when it ended its spin-up there, which is determined by the parameters, e.g., accretion rate and radius.[29,30] The observations of x-ray binaries, which are the progenitor systems of pulsars,[31,32] indicate that most massive binary systems are accreting at a rate $\dot{M} \sim 0.1\dot{M}_{\rm Edd}$–$1\dot{M}_{\rm Edd}$, thus the radius of the recycled pulsar is estimated to be in the range of ∼8.14–25.74 km.

In summary, we have considered the simple case of the moment of inertia for NS uniform density, $I = \frac{2}{5}MR^2$. The general case $I = \alpha MR^2$ is discussed, where the parameter α is less than its maximum value of $0.4\,(=2/5)$, based on which we obtain the new constraint of the DNS radius as $\hat{R} = (\frac{\alpha}{0.4})^{-1/2}R$. If $\alpha = 0.4$, we should obtain our previous result; if $\alpha = 0.3$, we should obtain $\hat{R} = 1.2R$, i.e., the new result presents about 20% increase compared to our previous value. Since the EOS of NS has not yet been known, we cannot evaluate the exact value of α. However, the result of radius based on the I value for uniform density is the lower limit of DNS. As for the estimation of NS radius by the x-ray burst, it is a good method, which targets at the NSs in LMXB systems with the type-I x-ray bursts. In our case, DNS is formed in the HMXB system, and we are exploiting the radius observation data to estimate the DNS radius.

It has been assumed that most systems may accrete 0.1–$0.2\,M_\odot$ at the end of the accretion phase.[15] For some of the smaller accretion rates, e.g., $\sim 0.001\,M_\odot$–$0.01\,M_\odot$ of an NS, as a result of these processes, a recycled pulsar with mildly weak field and short spin period ($B \sim 10^{10}$ G, $P \sim 50$ ms) will be formed, like PSR B1913+16 and PSR J0737-3039.[2,33] At the end of the accretion phase (accreted mass greater than $0.2\,M_\odot$), we find that a situation in the magnetic field of an NS may arrive at a bottom value of about 10^8–10^9 G and its spin period may reach a minimum of about a few milliseconds. For this system, the recycled PSR A, whose period is shorter than 50 ms, we have explored accretion at rate of $0.01\,M_\odot$ through the stellar process onto the companion. Then the estimated range of accretion rate in the binary system would be as high as 0.1–1 the Eddington rate. Finally, the evolution of the surface dipole magnetic field strength B versus spin period $P_{\rm s}$ (B–P diagram) poses challenges in attaining deep analysis of their evolution track.

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References

[1] Burgay M et al 2003 *Nature* **426** 531
[2] Lyne A G et al 2004 *Science* **303** 1153
[3] Kramer M et al 2006 *Science* **314** 97
[4] Kramer M et al 2008 *Annu. Rev. Astron. Astrophys.* **46** 541
[5] Li X D and Wang Z R 1999 *Astrophys. J.* **513** 845
[6] Podsiadlowski Ph et al 2005 *Mon. Not. R. Astron. Soc.* **361** 1243
[7] Özel F et al 2016 *Astrophys. J.* **820** 28
[8] Özel F 2016 *Annu. Rev. Astron. Astrophys.* **54** 401
[9] Nomoto K 1984 *Astrophys. J.* **277** 791
[10] Ferdman R D et al 2013 *Astrophys. J.* **767** 85
[11] Bhattacharya D and van den Heuvel E P J 1991 *Phys. Rep.* **203** 1
[12] van den Heuvel E P J 2009 *Astrophys. Space Sci. Libr.* **359** 125
[13] Alpar M A et al 1982 *Nature* **300** 728
[14] Lorimer D R et al 2007 *Mon. Not. R. Astron. Soc.* **379** 1217
[15] Shapiro S L and Teukolsky S A 1983 *Black Holes, White Dwarfs and Neutron Stars* (New York: Wiley)
[16] Zhao H H and Song L M 2013 *Proceedings IAU Symposium* **290** 369
[17] Özel F et al 2012 *Astrophys. J.* **757** 55
[18] Camilo F et al 1994 *Astrophys. J.* **421** L15
[19] Ghosh P and Lamb F K 1979 *Astrophys. J.* **234** 296
[20] Miller M C 2002 *Nature* **420** 31
[21] Demorest P B et al 2010 *Nature* **467** 1081
[22] Antoniadis J et al 2013 *Science* **340** 1233232
[23] Li A et al 2012 *Astropart. Phys.* **37** 70
[24] Menezes D P et al 2006 *J. Phys.* G **32** 1081
[25] Zhang C M et al 2011 *Astron. Astrophys.* **527** A83
[26] Glendenning N K and Weber F 2001 *Astrophys. J. Lett.* **559** L119
[27] Chatziioannou K et al 2014 *Phys. Rev.* D **90** 064030
[28] Li X D and Wang Z R 1996 *Astron. Astrophys.* **311** 911
[29] Haensel P et al 2007 *Neutron Stars* (Berlin: Springer)
[30] Cottam J et al 2002 *Nature* **420** 51
[31] Zhang C M and Kojima Y 2006 *Mon. Not. R. Astron. Soc.* **366** 137
[32] Liu Q Z et al 2007 *Astron. Astrophys.* **469** 807
[33] Hulse R A and Taylor J H 1975 *Astrophys. J. Lett.* **195** L51