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Simulation of the orbit and spin period evolution of the double pulsars PSR J0737–3039 from their birth to coalescence induced by gravitational wave radiation

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Abstract The complete orbital and spin period evolutions of the double neutron star (NS) system PSR J0737–3039 are simulated from birth to coalescence, which include the two observed radio pulsars classified as primary NS PSR J0737–3039A and companion NS PSR J0737–3039B. By employing the characteristic age of PSR J0737–3039B to constrain the true age of the double pulsar system, the initial orbital period and initial binary separation are obtained as 2.89 h and 1.44×10^6 km, respectively, and the coalescence age or the lifetime from the birth to merger of PSR J0737–3039 is obtained to be 1.38×10^8 yr. At the last minute of coalescence, corresponding to the gravitational wave frequency changing from 20 Hz to 1180 Hz, we present the binary separation of PSR J0737–3039 to be from 442 km to 30 km, while the spin periods of PSR J0737–3039A and PSR J0737–3039B are 27.10 ms and 4.63 s, respectively. From the standard radio pulsar emission model, before the system merged, the primary NS could still be observed by a radio telescope, but the companion NS had crossed the death line in the pulsar magnetic-field versus period ($B - P$) diagram at which point it is usually considered to cease life as a pulsar. This is the first time that the whole life evolutionary simulation of the orbit and spin periods for a double NS system is presented, which provides useful information for observing a primary NS at the coalescence stage.

Key words: PSR J0737–3039 — double neutron star — pulsar — gravitational wave — simulation

1 INTRODUCTION

In 1974, Taylor and Hulse discovered the first double neutron star (DNS) system PSR J1913+16, using the Arecibo telescope (Hulse & Taylor 1975), by which, the existence of gravitational waves (GWs) as a prediction of general relativity was indirectly verified by studying its orbital contraction (Einstein & Sitzungsber 1916; Taylor & Weisberg 1982). More than 40 years later, for the first time, LIGO and Virgo detected a GW, named GW170817, directly in the merger of a DNS system in an old elliptical galaxy. Together with a series of discoveries about the coalescence between stellar black holes and neutron stars (NSs), GW theory has been confirmed and the field of multi-messenger astronomy was born (Abbott et al. 2017; Troja et al. 2017; Blanchard et al. 2017). Therefore, investigation of the whole evolutionary process of a DNS system from its birth to coalescence and clarifying the details of its evolution are matters of concern to some scientists working on NS and pulsar astrophysics.

Among the 19 DNS systems that have been discovered until now, PSR J0737–3039 is the only known DNS system in which the primary and companion NSs have been detected as pulsars (Burgay et al. 2003; Lyne et al. 2004), which can not only provide the best direct test for the correctness of general relativity, but can also be employed as a natural lab for studying plasma physics and strong field gravitation (Kramer et al. 2004; Kramer et al. 2006; Kramer & Wex 2009). Among the 19 DNSs, only PSR J0737–3039 can provide more information about the initial orbital and initial NS spin periods, therefore the PSR J0737–3039 system can be studied as a test case for the evolution of DNS systems from their birth to merger. PSR J0737–3039 has a very compact orbit with an orbital period of only 2.45 h, and the eccentricity is as small as 0.088 (approximately a circular orbit) (Lyne et al. 2004). From the model of DNS formation (Bhattacharya & van den Heuvel 1991; van den Heuvel 2004), the primary NS (PSR J0737-3039A) was the first NS to be formed, generated by a massive star directly through a supernova explosion and it experienced accretion induced spin-up and magnetic field decay, with a spin period of 22.7 ms and dipole magnetic field of 6.4×10^9 G (Lyne et al. 2004); the companion NS (PSR J0737–3039B) was the second NS produced by the two methods of an electron capture supernova explosion (Podsiadlowski et al. 2004; Nomoto 1984) and ultra-stripped supernova explosion (Tauris et al. 2013, 2015, 2017), with the spin period and dipole magnetic field of 2773.46 ms and 6.4×10^9 G, respectively (Lyne et al. 2004).

As expected, the orbits of the DNSs are contracting continuously by GW radiation and will eventually merge, the direct coalescence observation and calculations of which were pointed out by Schutz (Schutz 1986), and by Cutler (Cutler et al. 1993). Now, numerical relativity is a very powerful tool for studying DNS orbital evolution, when the DNS system enters its merger (Maione et al. 2016; Shibata & Uryū 2000). In order to study the complete evolution of PSR J0737–3039, we deduced the variation of the orbital period given by Peters (1964) to obtain a new evolution formula and applied it to simulate the orbital evolution of DNS. Since PSR J0737–3039B is a non-recycled pulsar like the Crab Pulsar (Lyne & Graham-Smith 2012; Yang et al. 2017), and the current spin period is much larger than its initial spin period, we can rely on its characteristic age to approximate the true age of the PSR J0737–3039 system (Camilo et al. 1994; Lorimer et al. 2007). Next, we derived the initial orbital period of the system and the initial spin periods of the two pulsars, based on which the simulation of complete evolution of the system is presented.

The paper is organized as follows: In Section 2, we introduce the orbital evolution formula for DNS caused by gravitational radiation, then the simulation of the complete orbital evolutions of PSR J0737–3039 system is provided in Section 3. We simulate the entire spin period evolution of PSR J0737–3039A and PSR J0737–3039B in Section 4. Finally, we simulate the GW frequency of the last minute before the DNS merger, and then discuss the results.

2 ORBITAL EVOLUTION OF DOUBLE NEUTRON STARS

In this section, we derive the contraction evolution of a DNS orbit by GW radiation, based on variation of the orbital radius (a) of a DNS system, which is given below (Peters 1964; Lyne & Graham-Smith 2012; Shapiro & Teukolsky 1983; Lightman et al. 1975; Lightman & Shapiro 1975; Ohanian & Ruffini 1994)

$$\frac{1}{a}\frac{da}{dt} = -\frac{64}{5}\frac{G^3M^2\mu}{c^5a^4}f(e), \quad (1)$$

where M is the total mass of DNS, expressed as $M = M_p + M_c$ with M_p and M_c being the mass of the primary and companion NS, respectively; G (c) is the gravitational constant (speed of light); μ is the reduced mass of DNS, expressed as: $\mu = M_pM_c/(M_p + M_c)$; $f(e)$ is a function of the orbital eccentricity e of DNS, described in the following (Peters & Mathews 1963):

In this paper, we only consider the case of a circular orbit $e = 0$ because the eccentricity of PSR J0737–3039 is 0.088, which causes the eccentricity function to be $f(e = 0) = 1$.

$$f(e) = (1 + \frac{73}{24}e^2 + \frac{37}{96}e^4)(1 - e^2)^{-\frac{7}{2}}. \quad (2)$$

According to the Keplerian motion, the relationship between the DNS orbital period and the binary separation is

$$P = (\frac{a^3 4\pi^2}{GM})^{\frac{1}{2}}, \quad (3)$$

thus the orbital evolution can also be equivalently described by the orbital period. We insert Equation (2) and Equation (3) into Equation (1) and solve the evolution of DNS binary separation with time, and obtain the following equation

$$a = a_0(1 - \frac{t}{T_{\rm gw}})^{\frac{1}{4}}, \quad (4)$$

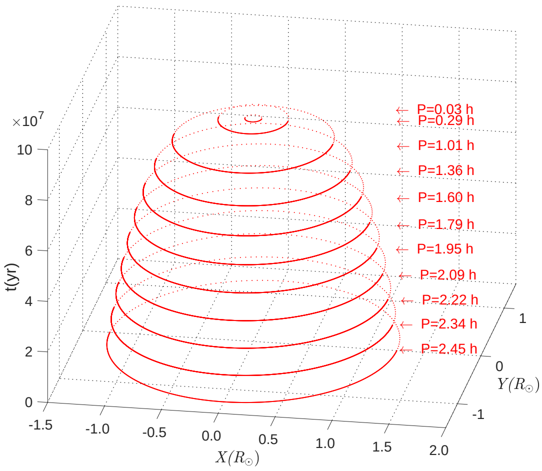

Fig. 1 Three-dimensional diagram of PSR J0737–3039's evolutionary trajectory by GW radiation, where the vertical axis stands for time in the unit of 10^7 yr and two horizontal axes of the orbital plane represent the DNS orbit, with the unit of radius being the Sun, $R_\odot = 7 \times 10^{10}$ cm.

where a_0 is initial binary separation of DNS, and $T_{\rm gw}$ is a characteristic time of GW induced coalescence, expressed as

$$T_{\rm gw} = \frac{5}{32}\frac{Ma_0^4}{\mu c R_s^3}, \quad (5)$$

with the Schwarzschild radius $R_s = 2GM/c^2$.

From Equation (3) and Equation (4), we can also deduce the relationship between orbital period and time as follows

$$P = P_0(1 - \frac{t}{T_{\rm gw}})^{\frac{3}{8}}, \quad (6)$$

with P_0 the initial orbital period.

Now that we have the evolutionary equations of orbital scale and period induced by the GW radiation, detailed simulations of double pulsars can be performed. PSR J0737–3039 is a DNS system where two pulsars were discovered by the pulsar search of the Parkes 64 m radio telescope in 2003, and lie at a distance of $1.15^{+0.22}_{-0.15}$ kpc (Burgay et al. 2003; Lyne et al. 2004). The parameters of two NSs are noted below: PSR J0737–3039A is an old, fast-spinning, recycled pulsar, with mass of 1.3381 $M_\odot$, spin period of 22.7 ms and spin period derivative of 1.76×10^{-18} s s^{-1} (Lyne et al. 2004); PSR J0737–3039B is a slowly spinning, non-recycled normal pulsar with a mass of 1.2489 $M_\odot$, spin period of 2773.46 ms and the spin period derivative is 8.29×10^{-16} s s^{-1} (Burgay et al. 2003). This system also has the shortest orbital period of 2.448 h among 19 pairs of DNSs, and the orbital eccentricity is as small as 0.088, an almost circular orbit (Burgay et al. 2003). Moreover, the system displays a strong relativistic effect, as the orbit is confirmed to shrink by GW radiation during the evolution process (Kramer & Wex 2009; van Leeuwen et al. 2015; Abbott et al. 2009).

Here, we simulate the orbital evolution of PSR J0737–3039 before the two NSs merge, where we assume that the two NSs are point particles with a nearly circular orbit. Then, during the simulation, we assume that the DNS system begins to merge when the orbital radius decays to the scale of two NS radii, 30 km, considering the conventional NS radius to be 15 km. Our simulation found that the merger age of the PSR J0737–3039 system is 8.83×10^7 yr, and the maximum orbital frequency of the system before the merge is 590 Hz, corresponding to a GW frequency of 1180 Hz. A schematic diagram of orbital evolution of PSR J0737–3039 is plotted in Figure 1, where we draw a complete cycle of trajectory motion in every time interval of 10^7 yr between $0 - 8 \times 10^7$ yr, and also include 8.8×10^7 yr and 8.83×10^7 yr, and each trajectory gives the corresponding orbital period.

3 EVOLUTION OF THE PSR J073–3039 SYSTEM IN ITS COMPLETE COALESCENCE AGE

Based on the magnetic dipole radiation model of a pulsar (braking index t = 3) (Lorimer et al. 2007; Shapiro & Teukolsky 1983), we make a simple integral calculation for the pulsar spin-down model ($\dot{P}_s \propto P_s^{2-n}$), deriving the relationship among the true age (t), spin period (P_s), spin period derivative ($\dot{P}_s$) and initial spin period (P_{s0}) of the pulsar, which can be written as (Lorimer et al. 2007; Shapiro & Teukolsky 1983; Zhang et al. 2016)

$$P_s^2 = P_{s0}^2 + 2t[P_s\dot{P}_s]. \quad (7)$$

Since a normal pulsar (e.g., PSR J0737–3039B) does not experience the accretion precess, its initial spin period is much smaller than its current spin period ($P_{s0} \ll P_s$), and we can approximately transform Equation (7) as

$$t \simeq \frac{P_s}{2\dot{P}_s} \equiv \tau, \quad (8)$$

where τ is the current characteristic age of the pulsar, expressed as $\tau \equiv P_s/(2\dot{P}_s)$. The above formula indicates that we can use the characteristic age of a pulsar to approximately replace its true age (when $P_{s0} \ll P_s$) (Lorimer et al. 2007; Camilo et al. 1994). This means that the age of the PSR J0737-3039 system is approximately equal to the current characteristic age of PSR J0737-3039B.

Compared to PSR J0737–3039A that experienced the accretion recycling process, PSR J0737–3039B is a relatively young normal pulsar with a spin period of 2773.46 ms and characteristic age of 4.92×10^7 yr (Burgay et al. 2003). Similar to the Crab Pulsar that has constant magnetic field dipole radiation (Staelin & Reifenstein 1968), we assume that the initial spin period of PSR J0737-3039B is 20 ms (Zhang et al. 2016), because the current spin period is much larger than the birth spin period ($20\ {\rm ms} \ll 2773.46\ {\rm ms}$), consequently the true age of PSR J0737-3039B (t_B) can be approximated by the characteristic age (τ_B), namely

$$t_B \simeq \tau_B. \quad (9)$$

Lorimer et al. (2007) pointed out that when PSR J0737–3039A ceased to spin-up and the birth of PSR J0737–3039B occurred at almost the same time (Lorimer et al. 2007), the spin-down age of PSR J0737–3039A (time since the accretion induced spin-up stopped: t_A) can be approximately replaced by the true age of PSR J0737–3039B, that is

$$t_A = t_B \simeq \tau_B. \quad (10)$$

According to the standard DNS formation model (van den Heuvel 2007), the first NS of the

Table 1 Parameters of Double Pulsar PSR J0737–3039 (Lyne et al. 2004; Burgay et al. 2003)

System	$M_p(M_\odot)$	$M_c(M_\odot)$	P (h)	P_s (ms)	d (kpc)	eccentricity	τ (yr)	$\dot{P}_s$ (s/s)	B (G)
J0737–3039A	1.3381(7)	....	2.448	22.699	$1.15^{+0.22}_{-0.15}$	0.088	2.04×10^8	1.76×10^{-18}	6.4×10^9
J0737–3039B	....	1.2489(7)	....	2773.46	....	....	4.92×10^7	8.29×10^{-16}	1.59×10^{12}

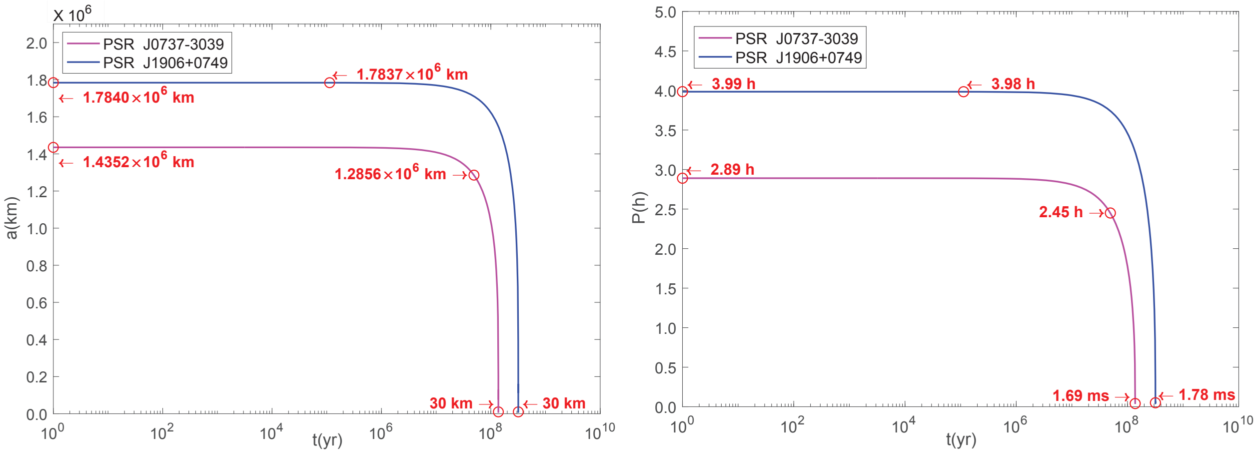

Fig. 2 The orbital evolution of double pulsar system PSR J0737–3039. As a comparison, PSR J0737–3039 and PSR J1906+0749 are indicated.

system was formed by a massive star undergoing main sequence evolution and supernova explosion. The first NS will accrete matter from the progenitor star of the companion star (B), which will spin-up the period of the first NS; If the system survives the second supernova explosion, the DNS system will be born at this moment. Hence the true age of the DNS system is equal to the true age of the second NS, and the true age of PSR J0737–3039 system (t_{AB})

$$t_{AB} = t_B \simeq \tau_B. \tag{11}$$

From the above formula we can constrain the real age of the PSR J0737–3039 system to be 4.92×10^7 yr, and the system will reach its coalescence age (time from birth to merger) in approximately 1.38×10^8 yr (the characteristic age of PSR J0737–3039B is 4.92×10^7 yr and the coalescence age of the system will be 1.38×10^8 yr).

We insert the age of the PSR J0737–3039 system t_{AB} into Equation (4) and Equation (6), and obtain the initial binary separation of the system to be 1.44×10^6 km, corresponding to the initial orbital period of 2.89 h, which means that the binary separation and orbital period of the system only contracted by 0.15×10^6 km and 0.44 h, respectively (the present binary separation and orbital period are 1.29×10^6 km and 2.45 h, respectively). Next, based on initial information on the PSR J0737–3039 system, we simulated the evolution of the orbital period and binary separation of PSR J0737–3039 within the complete coalescence age, as shown in Figure 2.

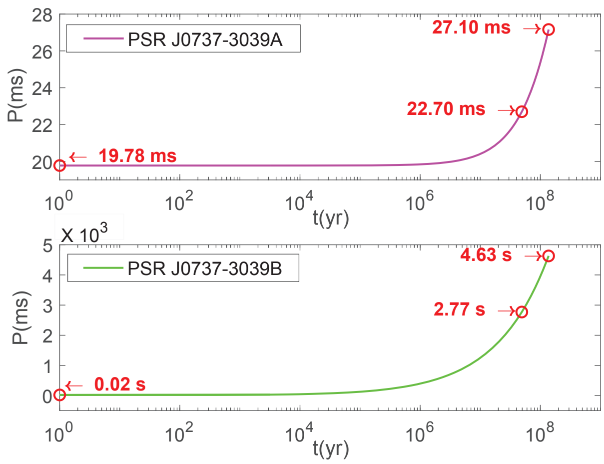

Fig. 3 Spin period evolutions of PSR J0737-3039A and PSR J0737–3039B.

3.1 The Spin Evolutions of PSR J0737–3039A and PSR J0737–3039B at the Complete Coalescence Age

We apply the observational data of PSR J0737–3039A and t_A to Equation (7), ascertaining that the birth spin period is 19.78 ms when it starts to spin-down, which means that its spin period only increased by 2.92 ms (the present spin period is 22.70 ms). From the above, the initial spin period of PSR J0737–3039B is assumed to be similar to that of the Crab Pulsar of 20 ms, compared to its current period of 2773.46 ms, thus the spin period of PSR J0737–3039B has evolved relatively quickly.

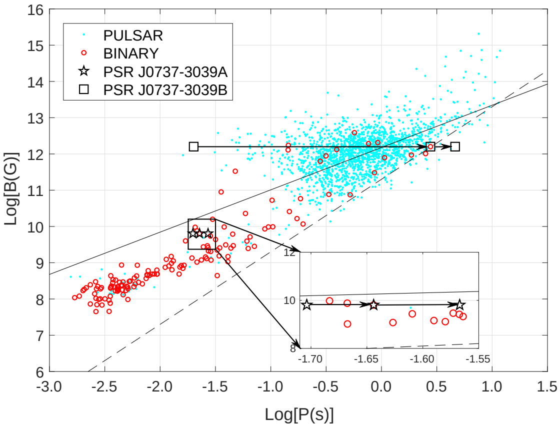

Fig. 4 The evolution tracks of PSR J0737–3039A and PSR J0737–3039B along the $B-P$ diagram (data from ATNF Pulsar Catalog (Manchester et al. 2005). The cyan dots, red circles, black lines, black dashed lines, pentagrams and squares represent normal pulsars, binary pulsars, acceleration lines, death lines, PSR J0737–3039A and PSR J0737–3039B, respectively.

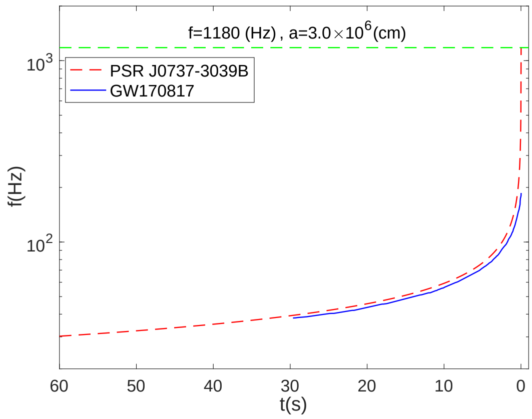

Fig. 5 The evolution of GW frequency at the last minute of DNS merger, where the dashed (solid) curve represents the case of PSR J0737–3039 (GW170817).

In order to simulate the evolution of the pulsar spin-down, we assume that the dipole magnetic field is invariant during the evolution, therefore we can transform Equation (7) as

$$P_s^2 = P_0^2 + 2t[P_n\dot{P}_n], \tag{12}$$

where P_n and $\dot{P}_n$ are the current measured data of the pulsar spin period and spin period derivative, respectively.

According to Equation (12), we simulated the spin period evolution of PSR J0737-3039A and PSR J0737–3039B within the complete merger age, and stopped the simulation when the evolution time reached 1.38×10^8 yr. Our simulation found that: the spin periods of PSR J0737–3039A and PSR J0737–3039B are 27.10 ms and 4.63 s, respectively, when the system merged. Based on the simulation results, we plot the spin period evolutions of PSR J0737–3039A and PSR J0737–3039B in Figure 3.

In order to understand the complete scenario for the evolution of both pulsars in the diagram of spin period and magnetic field (the magnetic fields of PSR J0737–3039A and PSR J0737–3039B are 6.4×10^9 G and 1.59×10^{12} G, respectively, Burgay et al. 2003; Lyne et al. 2004), we plot their complete simulation results in Figure 4.

In Figure 4, the small box is a close-up of the evolution track of PSR J0737–3039A, and the arrows indicate the direction of evolution (the evolution from left to right means from birth to merger). It can be seen from the figure that from the system's birth to its merger, PSR J0737–3039A could always be seen by a radio telescope, but PSR J0737–3039B will cross the death line of a pulsar and may be not observable (Bhattacharya & van den Heuvel 1991).

4 THE RESULTS AND DISCUSSIONS

In this paper, based on observational data of the double pulsar system PSR J0737–3039, we simulated its orbital evolution induced by GW radiation, and found that the system will merge after 8.83×10^7 yr. By the magnetic dipole model of a pulsar, we concluded that the PSR J0737–3039 system will exist about 4.92×10^7 yr, thus the complete coalescence age (from its birth to merger) of the PSR J0737–3039 system should be 1.38×10^8 yr. Next, we simulated the complete orbital evolution of the PSR J0737–3039 system and obtained the initial orbital period and radius as 2.89 h and 1.44 km, respectively. In addition, the GW frequency generated within the last minute before the system merges ranges from 20 Hz to 1180 Hz, and the corresponding binary separation decays from 442 km to 30 km. We compared the GW frequency evolution of PSR J10737–3039 with that of the observational data of GW170817 by LIGO, as displayed in Figure 5, and found that both curves have not much difference, and a small bias is due to the mass difference of both systems (the primary NS and companion NS masses of GW170817 are: $1.46^{+0.12}_{-0.10}M_\odot$ and $1.27^{+0.09}_{-0.09}$, respectively, Abbott et al. 2019).

Furthermore, we calculated the spin period evolutions of PSR J0737–3039A and PSR J0737–3039B within the complete merger age, and found that their spin periods are 27.10 ms and 4.63 s at coalescence. Through the evolution trajectories of PSR J0737–3039A and PSR J0737–3039B in the pulsar magnetic field and spin period $B-P$ diagram, we concluded that PSR J0737–3039A can always be observed by radio telescopes, but PSR J0737–3039B will cross the death line of radio pulsars and might not be observable.

It is remarkable that we employed the point masses of both NSs to perform the simulation. However, Kuznetsov et al. (1998) studied the orbital evolution of DNS by considering GW radiation but the internal structures of NSs have been taken into account, and they pointed out that there is little effect on their merging time (only deviating by 10.5 ms) (Kuznetsov et al. 1998), which is much less than the merging time of 30 s as observed in GW170817 by LIGO.

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