Early Phases of Different Types of Isolated Neutron Star

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Abstract

Two Galactic isolated strong X-ray pulsars seem to be in the densest environments compared to other types of Galactic pulsar. X-ray pulsar J1846-0258 can be in an early phase of anomalous X-ray pulsars and soft gamma repeaters if its average braking index is ∼1.8-2.0. X-ray pulsar J1811-1925 must have a very large average braking index (∼11) if this pulsar was formed by SN 386AD. This X-ray pulsar can be in an early phase of the evolution of the radio pulsars located in the region P∼50-150 ms and $\dot{P}$∼10^{-14}-10^{-16} s/s of the P-$\dot{P}$ diagram. X-ray/radio pulsar J0540-69 seems to be evolving in the direction to the dim isolated thermal neutron star region on the P-$\dot{P}$ diagram. Possible progenitors of different types of neutron star are also discussed.

Keywords: neutron star – pulsar: J1846-0258, J1811-1925, J0540-69 – pulsar: evolution

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1 Introduction

There are several different types of isolated neutron star: radio pulsars some of which also radiate in other bands of the electromagnetic spectrum; dim radio quiet neutron stars (DRQNSs) which are dim in X-rays, not detected in radio band and all of which are connected to supernova remnants (SNRs); dim isolated thermal neutron stars (DITNSs) which are also dim in X-rays and not detected in the radio, and which have long spin period (P) contrary to DRQNSs (except Geminga which has short spin period but which shows DITNS characteristics); anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs) which have $L_X/\dot{E}>1$ (where L_X is the X-ray luminosity and $\dot{E}$ is the rate of rotational energy loss) with long spin periods and which show gamma ray bursts and X-ray flares.

Radio pulsars are believed to be born on the upper-left part of the P-$\dot{P}$ diagram and evolve to the right part. Some radio pulsars (some of which have also been detected in X-rays) are located on the lower-left part of the diagram (see Fig.1). The birth locations of these pulsars on the diagram is an open question. More importantly, the birth locations of SGRs/AXPs and DITNSs on the diagram are also unclear. If we can identify some sources which are younger appearances of these different types of neutron star, we can guess where they come from on the diagram, and furthermore, we can have more information on different characteristics of these neutron stars.

There are 2 Galactic isolated pulsars which have some different characteristics compared to other isolated pulsars. These 2 pulsars are J1846-0258 (P=0.32359795 s, $\dot{P}$=7.09706$\times 10^{-12}$ ss^{-1}, which is connected to SNR Kes 75 [1,2]) and J1811-1925 (P=0.064667 s, $\dot{P}$=4.40$\times 10^{-14}$ ss^{-1}, which is connected to SNR G11.2-0.3 [1,2]). Both of these pulsars have been identified as X-ray pulsars with strong X-ray emission compared to DRQNSs and DITNSs, but none of them has been detected in radio band. They seem to have very dense environments [3]. In addition to these 2 X-ray pulsars, there is a pulsar in Large Magellanic Cloud (LMC) which has strong X-ray emission but which is very dim in radio band. This pulsar (J0540-69) also seems to have a very dense ambient medium.

In Section 2, the observational data of these pulsars and their SNRs are examined and the possibility that these pulsars can be in early phases of different types of neutron star is discussed. In Section 3, conclusions are given.

2 Three isolated strong X-ray pulsars in very dense media

2.1 X-ray pulsar J1846-0258; early phase of SGR/AXP

The position of J1846-0258 on the P-$\dot{\text{P}}$ diagram together with its possibly small average braking index (n=1.86±0.08 with the assumption of no glitch and/or significant timing noise [4]) suggest that this pulsar may be in a phase preceding SGRs/AXPs (Fig.1). The X-ray luminosity of J1846-0258 is on the order of 10^{35} erg/s [5,6] which is typical for SGRs/AXPs. Moreover, the $L_X/\dot{\text{E}}$ value is ∼0.016 [2,6] which is very large compared to radio pulsars (more than 6 times larger than $L_X/\dot{\text{E}}$ value of Crab pulsar). For SGRs/AXPs $L_X/\dot{\text{E}} > 1$ (the name 'anomalous' comes from this fact) and if the X-ray luminosity of J1846-0258 does not drop significantly in the next ∼10^4 yr its $L_X/\dot{\text{E}}$ value will be similar to those of SGRs/AXPs.

Even if J1846-0258 has n=2-2.5 (n=2 corresponds to constant $\dot{\text{P}}$) because of some glitches, this pulsar comes to a position above the position of AXP 2259+586 and probably above the positions of DITNSs assuming that the three DITNSs for which only the upper limits on $\dot{\text{P}}$ are known have positions close to the position of J0720.4-3125 on the P-$\dot{\text{P}}$ diagram (Fig.1).

According to Blanton & Helfand [7] SNR Kes 75 (G29.7-0.3) has an age ∼10^3 yr. It is better to adapt the age of the pulsar (which can be ∼1700 yr) as the age of Kes 75 – J1846-0258 pair considering the possibly small value of n of the pulsar and also the large diameter of the SNR [6]. For n=2 (i.e. for constant $\dot{\text{P}}$), J1846-0258 can reach to a spin period ∼2.5 s in 10^4 yr. Ages of the SNRs connected to AXPs are a few times 10^4 yr [3]. In (2-5)×10^4 yr J1846-0258 can come to the region of AXPs/SGRs on the P-$\dot{\text{P}}$ diagram.

J1846-0258 seems to be in a very dense medium [3] and SNR Kes 75 is expanding into a higher density medium on its far side [8]. As suggested by Guseinov et al. [3] the progenitor of J1846-0258 can be an O-type star.

In Guseinov et al. [9,10] the idea of possible existence of low-mass neutron stars has been introduced to explain the positions and possible evolution of SGRs/AXPs on the P-$\dot{\text{P}}$ diagram without any need for very high magnetic field (B≤10^{14} G). Magnetic dipole radiation of neutron stars is given as [11]

$$L = \frac{2}{3}\frac{\mu^2\omega^4}{c^3}Sin^2\beta = \frac{2}{3}\frac{B_r^2R^6\omega^4}{c^3}Sin^2\beta \qquad (1)$$

where μ is the magnetic moment, ω the angular velocity, c the speed of light, β the angle between the rotation axis and the magnetic field axis, B_r the real dipole magnetic field and R the radius of neutron star. On the other hand, the rate of rotational energy loss of spherically symmetric neutron stars which have rigid body rotation is given as

$$\dot{E} = \frac{4\pi^2 I \dot{P}}{P^3} \tag{2}$$

where I is the moment of inertia, P the spin period of pulsar, and $\dot{P}$ the time derivative of P. From expressions (1) and (2) we get

$$\dot{P} \propto \frac{B_r^2 R^4}{MP} \tag{3}$$

where M is the mass of pulsar. So, a neutron star with M$\sim$0.5-0.7 M$_\odot$ must have $\sim$4-9 times larger $\dot{P}$ compared to a neutron star with M$\sim$1.4-1.5 M$_\odot$ if both neutron stars have the same B_r and P values (considering also the increase in R when M is smaller). For such a low mass neutron star the propeller mechanism can work more efficiently to spin down the pulsar in relatively very short time and the reconnection of the magnetic field can occur more easily to produce the γ-ray bursts.

X-ray pulsar J1846-0258 can be such a low mass pulsar. Its possibly small n and its position on the P-$\dot{P}$ diagram support the low-mass neutron star idea. Moreover, the X-ray luminosity and the present $L_X/\dot{E}$ value of this X-ray pulsar further suggest that it can be in a phase preceding SGR/AXP phase. Also, J1846-0258 is an isolated X-ray pulsar without any detected radio emission similar to SGRs/AXPs. Besides, such low mass neutron stars must have $B_{initial} = 3\times10^{13}$ - 10^{14} G [9,10]; J1846-0258 is only $\sim$1700 yr old and its B=5×10^{13} G. If J1846-0258 is the former appearance of all SGRs/AXPs, then we can say that such objects must have O-type progenitors.

In Guseinov et al. [12] SGRs/AXPs were claimed to be in active stages of their evolution and they predicted that these sources would spend some time in passive stages (i.e. they must become unobservable occasionally). XTE J1810-197 has recently been identified as a transient AXP and it was seen that this source was unobservable in the past [13] proving the prediction of Guseinov et al.

So, this type of neutron star is possibly born with $P_0\sim$10-30 ms and evolves to the right part of the P-$\dot{P}$ diagram either with increasing $\dot{P}$ or with

$\dot{P}$∼const. as an isolated strong X-ray pulsar. It reaches to the SGR/AXP region in (2-5)×10^4 yr and shows γ-ray bursts and X-ray flares. Occasionally, it drops to a passive state and its luminosity drops significantly that it becomes unobservable.

The lack of any detected radio emission from X-ray pulsar J1846-0258 and from SGRs/AXPs can be due to the existence of ionized gaseous wind which must suppress the radio pulsar phenomenon when their periods are very small (in less than ∼10^3 yr).

2.2   X-ray/radio pulsar J0540-69; early phase of DITNS

X-ray/radio-dim pulsar J0540-69 in LMC is one of the youngest and most luminous rotation powered pulsars [14]. It was first observed as a 50 ms X-ray pulsar [15] and later it was detected as a faint radio pulsar with a 640 MHz flux ∼0.4 mJy [16]. It's $\dot{P}$ value is 4.8×10^{-13} s/s [14].

The average braking index of this pulsar is small (n∼2.2 [17]) that it comes to a position close to DITNS RX J0720.4-3125 in ∼10^6 yr which must be about the age of DITNS RX J0720.4-3125 (∼cooling age). Because of this, J0540-69 can be in a former phase of at least some of the DITNSs.

Similar to J1846-0258, $L_X/\dot{E}$ of J0540-69 is large compared to radio pulsars [6]. When J0540-69 reaches to a position close to the present position of RX J0720.4-3125 (which has $L_X/\dot{E}$ ∼ 10), it will have $L_X/\dot{E} > 1$.

There is a pre-SN ring around J0540-69 similar to the rings around SN1987A and the hourglass nebula around the blue supergiant Sher 25 [18]. The pulsar is connected to oxygen-rich SNR 0540-6944 [19]. There is a CO cloud located to the west of the remnant but it is not clear if the SNR is interacting with it or not [19]. The region surrounding the SNR has a rich HI structure [19]. The pre-SN ring around this pulsar similar to the rings seen around SN1987A [18] and its dense environment suggest that the progenitor of this pulsar must be an O-type star.

2.3   X-ray pulsar J1811-1925; large braking index

X-ray pulsar J1811-1925 is in a very dense medium [3]. The swept-up mass is 3-4 $M_\odot$ [20,21] and the ejected mass should be considerably larger than the swept-up mass [22]. SNR G11.2-0.3 is similar to SNR Cas A in this sense and the progenitor of it must be an O-type star (possibly early O-type).

The spin down age of pulsars can be calculated as

$$t = \frac{P}{(n-1)\dot{P}}[1 - (\frac{P_0}{P})^{n-1}] \qquad (4)$$

where P_0 is the initial spin period of pulsar. SNR G11.2-0.3 is probably related to the supernova (SN) of 386AD [2,23]. If J1811-1925 is the compact remnant of SN 386AD, then its age (t) is 1618 years. Then, if its $P_0 \sim 62$ ms [2,24], its n must be ~ 11. If P_0 is less than 62 ms, then n must be larger than 11. For n=3 and P_0=62 ms, t is about 1970 years. If n=3 and t=1618 years, then P_0 must be 0.064666999929 s (i.e. very close to the present P value of J1811-1925, which is 0.06466700 s). This is not possible because the present $\dot{P}$ value of J1811-1925 is 4.40E-14 s/s and in 1618 years there must be a change in the P value at least in the third digit after the decimal point unless n is much less than 2. So, the realistic values are: t=1618 yr, $P_0 \sim 62$ ms, $n \sim 11$. With such a braking index, J1811-1925 can reach to its present position (P=0.06466700 s and $\dot{P}$=4.40E-14 s/s) on the P-$\dot{P}$ diagram in 1618 years starting with $P_0 \sim 62$ ms.

So, this pulsar seems to be evolving downwards on the P-$\dot{P}$ diagram with a sharp decrease in $\dot{P}$ and very small increase in P. Radio/X-ray pulsars in the region $\tau = 10^5$ - 2×10^7 yr are displayed in Figure 1. Most of such pulsars are located on the lower left part of the diagram. On this part of the diagram, there are also some radio pulsars which have not been detected in X-rays. X-ray pulsar J1811-1925 seem to be evolving in the direction to the region of these radio/X-ray and radio pulsars. X-ray luminosity of J1811-1925 is $\sim 10^{33}$-10^{34} erg/s and the X-ray luminosity of the radio/X-ray pulsars in this region is 10^{30}-10^{34} erg/s [25,26].

The large n value of J1811-1925 indicates that either there is magnetic field decay (see Geppert & Rheinhardt [27] for the magnetic field decay in neutron stars and see Bisnovatyi-Kogan [28] for a review on magnetic field of neutron stars in general) or the angle between the spin axis and the magnetic field axis is decreasing sharply.

The lack of detected radio emission from J1811-1925 may be due to selection effects (luminosity function or beaming fraction) or maybe the radio emission of this X-ray pulsar is screened by some dense plasma around it.

AXP 1E 2259+586 is connected to SNR CTB 109 and the age of this SNR is $\sim 10^4$ yr [29−31] that AXP 1E 2259+586 has $n \sim 40$. Note that J1811-1925 must have such a very large n if it has $P_0 \sim 10$ ms which is generally

assumed to be a typical P_0 value for radio pulsars. Although they may have similar slope of tracks on the P-$\dot{P}$ diagram, note that AXP 1E 2259+586 and J1811-1925 are located on very different parts of the P-$\dot{P}$ diagram (see Fig.1) that their origins must be different.

2.4   A comparison between J1846-0258, J1811-1925, and J0540-69

All these 3 pulsars must have O-type progenitors. The progenitors of J1811-1925 and J0540-69 can be more massive than the progenitor of J1846-0258, and possibly the progenitor of J1811-1925 can be more massive than the progenitor of J0540-69. Since their positions on the diagram and their braking indices seem to be very different compared to each other, different physical processes must be dominant for each of them. Mass of the neutron star can be the main parameter for different physical processes to occur. Other than the mass of the progenitor, closeness of the binary and mass of the companion star before the SN explosion (i.e. before the disruption of the binary system), and the fact that the progenitor might be isolated must be considered to understand the formation of different types of neutron star.

If the progenitors of these 3 pulsars had actually very different zero age main sequence mass values compared to each other, these pulsars may have very different masses compared to each other. Differences in their n and $\dot{P}$ values, and their positions on the diagram together with the observational data about their environments support this idea. Among these 3 pulsars, J1846-0258 has the largest $\dot{P}$ (comparable to some AXPs) and the smallest n value that it may have the smallest mass (possibly $\sim$0.5-0.7 $M_\odot$). Similarly, J0540-69 may be less massive than J1811-1925.

X-ray pulsars J1846-0258 and J1811-1925 are two extreme cases and their initial parameters must be very different compared to each other. Differences in their mass and initial magnetic field (or $\dot{P}_{initial}$) values must be the main factors for the significant difference between their evolutions. These differences must be the cause of the difference between their n values; in the case of J1846-0258, the neutron star may have smaller mass and larger radius (extended atmosphere) and higher initial magnetic field so that it has large (and possibly increasing) $\dot{P}$, whereas in the case of J1811-1925, the neutron star must have lower initial magnetic field and possibly much more massive

than J1846-0258 that its B value drops sharply due to either magnetic field decay or a decrease in the angle between the magnetic field and the spin axes.

In order to understand if some of these pulsars evolved through massive binaries, central regions of the SNRs connected to these 3 pulsars must be examined to see if there are O or B-type stars present which are connected to the SNRs. Failing to find such OB stars may lead to the fact that the progenitors were either isolated or in binary systems with later type companions, but also note that the sources being located at large distances can make it difficult to realize the presence of such OB stars.

3   Conclusions

X-ray pulsar J1846-0258 seems to be evolving to become SGR/AXP in $\sim 10^4$ yr. It can be a low-mass neutron star which has an O-type progenitor.

X-ray/radio pulsar J0540-69 can become a DITNS in $\sim 10^6$ yr. Its progenitor must also be O-type, possibly more massive than the progenitor of J1846-0258.

X-ray pulsar J1811-1925 has a small $\dot{P}$ which is decreasing sharply. This X-ray pulsar can be in a former phase of the radio/X-ray and radio pulsars on the lower left part of the P-$\dot{P}$ diagram (Fig.1). The progenitor of J1811-1925 must be an O-type star, possibly more massive than the progenitors of the other 2 pulsars.

Which type a neutron star will become must depend on its progenitor's mass and on the effects of the binary evolution. For the 3 pulsars examined in this work, mass of the progenitor may be the main parameter for the mass and hence the type of the neutron star.

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Figure Caption

Figure 1: Spin period vs. time derivative of spin period diagram of different types of pulsar. Filled circles represent Galactic X-ray pulsars J1846-0258 and J1811-1925, and X-ray/radio pulsar J0540-69 in LMC. Filled squares and open squares display SGRs and AXPs, respectively. Asterisks represent DITNSs (for 3 of them the upper limits on their $\dot{P}$ values are shown with arbitrary arrows). DRQNSs are displayed with sign '+'. Radio pulsars are shown as small dots. Radio/X-ray pulsars in the region $\tau = 10^5$ - 2×10^7 yr are shown with sign 'X'. B12-B14, E32-E38, and A3-A7 indicate B=10^{12}-10^{14} G, $\dot{E}$=10^{32}-10^{38} erg/s, and τ=10^3-10^7 yr, respectively. The P and $\dot{P}$ values of DITNSs are from Haberl [32] and the P and $\dot{P}$ values of radio/X-ray pulsars are from Becker & Aschenbach [25] and Possenti et al. [26]. All the other P and $\dot{P}$ values are from ATNF catalogue [1].

Period Derivative (s/s)

Period (s)

1e-010

1e-011

1e-012

1e-013

1e-014

1e-015

1e-016

0.1

1

10

B14

B13

A3

E38

B12

A5

E35

A7

E32

1846

0540

1811

2259

0720