Rotational Evolution of the Slowest Radio Pulsar, PSR J0250+5854

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Abstract

We apply theoretical spin-down models of magnetospheric evolution and magnetic field decay to simulate the possible evolution of PSR J0250+5854, which is the slowest-spinning radio pulsar detected to date. Considering the alignment of inclination angle in a 3D magnetosphere, it is possible that PSR J0250+5854 has a high magnetic field comparable with magnetars or/and high magnetic field pulsars, if a small inclination angle is considered. Our calculations show that similar long-period pulsars tend to have a relatively low period derivative in this case. In another case of magnetic field decay, calculations also show a possible connection between PSR J0250+5854 and high dipole-magnetic field magnetars. The evolutionary path indicates a relatively high spin-down rate for similar long-period pulsars.

Key words: pulsars: general – pulsars: individual (PSR J0250+5854) – stars: neutron

1. Introduction

More than 2600 pulsars have been observed since the first discovery of a pulsar (Hewish et al. 1968; Manchester et al. 2005). They are divided into different groups according to their observational properties (Harding 2013). The evolutionary connections between different groups of neutron stars are widely discussed with different ways. The rotating radio transients are scattered throughout the range of normal pulsars. The rotating radio pulsars: individual (PSR J0250+5854) – stars: neutron

To investigate the link between PSR J0250+5854 and other neutron stars, we respectively apply spin-down models of magnetospheric evolution and magnetic field decay to simulate its possible rotational evolutions and to explain its unusual observations. Besides, possible observational properties under these two cases are predicted.

2. Rotational Evolution in the Case of Magnetospheric Evolution

2.1. Spin-down Torque

It is generally accepted that a neutron star should be surrounded by a plasma-filled magnetosphere. There are particles accelerated in the magnetosphere. The radiation of particles will generate the observed pulsar emission. The outflowing particle winds will take away the rotational energy to spin down the pulsar. Meanwhile, the presence of plasma in the magnetosphere will also generate a torque to align the magnetic axis and the rotational axis (Michel & Goldwire 1970; Philippov et al. 2014). For an oblique rotator, the evolution equation is (Michel & Goldwire 1970; Philippov et al. 2014)

\[ I \frac{d\Omega}{dt} = K, \]

where \( I \) is the moment of inertia and a typical value of \( 10^{45} \text{ g cm}^2 \) is taken in the following calculations, \( \Omega \) is the angular velocity, and \( K \) is the torque working on the pulsar. For a spherical system, Equation (1) can be expressed as

\[ I \frac{d\Omega}{dt} = K_{\text{spin-down}}, \]

\[ I \frac{d\alpha}{dt} = -K_{\text{alignment}}, \]

where \( \alpha \) is the angle between the magnetic axis and the rotational axis (i.e., the inclination angle), \( K_{\text{spin-down}} \) is the
torque to spin down the pulsar, and $K_{\text{alignment}}$ is the torque to align the pulsar. According to the magnetohydrodynamic (MHD) simulations of pulsar magnetospheres (Spitkovsky 2006), the spin-down torque can be expressed as

$$K_{\text{spin-down}} = -k_0 \frac{\mu^2 \Omega^3}{c^3} (\sin^2 \alpha + k_1),$$

(4)

where $\mu = (1/2)BR_0^3$ is the magnetic dipole moment ($B$ is the polar magnetic field and $R$ is the radius of the pulsar), and $c$ is the speed of light. Generally, $k_0$ is a numerical factor and $k_1$ represents the effect of out-flowing particles and is model dependent. Comparisons between different MHD simulations were discussed in Tong & Kou (2017). Here, we take $k_0 \approx k_1 \approx 1$ for simplicity. As pulsar is spinning down, the ability of pair production will decrease (Ruderman & Sutherland 1975). For pulsars near the death line, the effect of death must be considered (Zhang et al. 2000; Contopoulos & Spitkovsky 2006). Contopoulos & Spitkovsky (2006) applied the effect of pulsar death to simulate the rotational evolution of pulsars. We employ their treatment of pulsar death, and Equation (2) could be expressed as

$$\frac{d\Omega}{dt} = -\frac{\mu^2}{c^3} \left\{ \sin^2 \alpha + \left( 1 - \frac{\Omega_{\text{death}}}{\Omega} \right) \right\} \frac{\Omega_{\text{death}}}{\sin^2 \alpha} \quad \text{if } \Omega > \Omega_{\text{death}},$$

$$= \frac{\mu^2}{c^3} \left\{ \sin^2 \alpha + \left( \frac{\Omega_{\text{death}}}{\Omega} - 1 \right) \right\} \quad \text{if } \Omega \leq \Omega_{\text{death}},$$

(5)

where $\Omega_{\text{death}} = 2\pi/P_{\text{death}}$ is the angular velocity when a pulsar dies, and the death period is defined as (Contopoulos & Spitkovsky 2006; Tong & Xu 2012)

$$P_{\text{death}} = 0.885 \left( \frac{B}{10^{12} \text{ G}} \right)^{1/2} \left( \frac{V_{\text{gap}}}{10^{13} \text{ V}} \right)^{-1/2} \text{ s},$$

(6)

where $V_{\text{gap}}$ is the potential drop of the acceleration gap. Equation (5) means that the pulsar is braked by the combination of magneto-dipole radiation and particle wind before its death, but only brakes from the magneto-dipole radiation after its death. Compared with the previous work of Contopoulos & Spitkovsky (2006), a factor of $\cos^2 \alpha$ is omitted here. As discussed in Tong & Kou (2017), it is a weighting factor between the magnetic dipole radiation and the magnetospheric particles. Besides, considering the result of the magnetospheric simulations (Spitkovsky 2006; Li et al. 2012), the $\cos^2 \alpha$ factor may not appear in the particle wind component.

As the two components of the spin-down torque are independent of the inclination angle when $\alpha = 0^\circ$ and $\alpha = 90^\circ$, the alignment torque and the spin-down torque can be related as $K_{\text{alignment}} = [K_{\text{spin-down}}(0^\circ) - K_{\text{spin-down}}(90^\circ)] \sin \alpha \cos \alpha$ (Philippov et al. 2014). Hence, Equation (3) could be expressed as

$$I \Omega \frac{d\Omega}{dt} = -\frac{\mu^2}{c^3} \Omega^3 \sin \alpha \cos \alpha.$$

(7)

2.2. Spin Down of PSR J0250+5854

As PSR J0250+5854 is located just below the death line on the $P$–$P$ diagram, its radio emission may tend to stop, and its period may be much close to the death period, $P_{\text{obs}} \ll P_{\text{death}}$. A magnetic field of $B \geq 1.276 \times 10^{12} P_{\text{obs}} (V_{\text{gap}} / 10^{13} \text{ V}) \text{ G}$ can be calculated from Equation (6). Hence, an upper limit on the inclination angle of $\alpha = 3\pi/4 (V_{\text{gap}}/10^{13} \text{ V})^{-1}$ can be calculated from Equation (5). Generally, $V_{\text{gap}} = 10^{13} \text{ V}$ is taken for normal pulsars (Contopoulos & Spitkovsky 2006), and the corresponding minimum magnetic field and maximum inclination angle are $7.06 \times 10^{12} \text{ G}$ and $35^\circ$, respectively. Because PSR J0250+5854 is still a radio-loud pulsar, an inclination angle of $2^\circ$ is assumed. The magnetic field could be calculated from Equations (5) and (6), which is about $7.1 \times 10^{12} \text{ G}$.

The coupled evolutions of inclination angle and rotation can be calculated from Equations (5) and (7). Choosing the current period and magnetic field, the evolutionary paths for different assumed ages are the same, but with different beginning points. To get an initial period smaller than 20 ms, an age of $2.7 \times 10^5 \text{ yr}$ is assumed, and the corresponding initial period and inclination angle are 15 ms and $88^\circ$, respectively. The evolutions of the inclination angle and rotation of PSR J0250+5854 are shown as solid lines in Figures 1 and 2. The solid triangle in Figure 1 represents the inclination angle of $2^\circ$ at its age of $2.7 \times 10^5 \text{ yr}$. Meanwhile, the solid triangles in Figure 2 represent the periods and period derivatives at ages of $10^3 \text{ yr}, 10^4 \text{ yr}, 10^5 \text{ yr}, 10^6 \text{ yr}, 10^7 \text{ yr}, 10^8 \text{ yr}$, respectively. The death period and age are about $23.6 \text{ s}$ and $2.1 \times 10^8 \text{ yr}$, respectively.

Different acceleration models yield the potential drops of the order of $10^{12} \text{ V}$. A constant potential model of $3 \times 10^{12} \text{ V}$ was taken for an approximate calculation (Ruderman & Sutherland 1975; Xu & Qiao 2001). Here, we discuss a relatively extreme case with $V_{\text{gap}} = 10^{12} \text{ V}$. Similarly, a minimum magnetic field of $7.06 \times 10^{12} \text{ G}$ and a maximum inclination angle of $36^\circ$ can be calculated from Equations (5) and (6). Lower magnetic fields could be calculated by giving larger inclination angles. However, the evolutionary trend stays almost the same. Considering the alignment of the inclination angle, as well as

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8 For pulsars near the death line, the effect of particle wind would decrease. Meanwhile, if the inclination angle is very small, their contributions on the braking torque from magneto-dipole radiation and particle wind are comparable. Hence, the changes in the magnetic field are small with different inclination angles.

9 It is generally accepted that the initial period of a pulsar is about tens of milliseconds. An initial period of 17 ms was predicted for the Crab pulsar according to its truly recorded age (Lyne et al. 2015).
Figure 2. Rotational evolutions of PSR J0250+5854 in the case of magnetospheric evolution in the $P$–$P$ diagram. The solid evolution line is for $(B = 7 \times 10^{14} \text{ G}, V_{\text{gap}} = 10^{13} \text{ V}, \alpha = 2)$ and the solid triangles represent the periods and period derivatives at ages of 10 yr, 100 yr, $10^3$ yr, $10^4$ yr, $10^5$ yr, and $10^6$ yr. The dashed line is for $(B = 10^{14} \text{ G}, V_{\text{gap}} = 10^{12} \text{ V}, \alpha = 7)$ and the hollow triangles represent the periods and period derivatives at ages of 10 yr, 100 yr, $10^3$ yr, $10^4$ yr, $10^5$ yr, $10^6$ yr, and $10^7$ yr, respectively. The large red point is the position of PSR J0250+5854. The black points are the positions of PSRs J1146–0258, J1119–6127, and J2144–3933, respectively. The dotted–dashed line is the pulsar death line based on curvature radiation from the vacuum gap (Zhang et al. 2000).

the pulsar’s position on the $P$–$P$ diagram, a small inclination angle is assumed for PSR J0250+5854. A magnetic field of $10^{14}$ G will be calculated if an inclination angle of $7^\circ$ is assumed. Different ages used just result in different starting points of the evolutionary line. Similarly, to get an initial period smaller than 20 ms, an age of $5.4 \times 10^7$ yr is assumed here. Coupled evolutions of the rotation and the inclination angle can be calculated from Equations (5) and (7). The initial inclination angle and rotational period are about 87.8 and 18 ms, respectively. Evolutions of the inclination angle and rotation of PSR J0250+5854 are shown as dashed lines in Figures 1 and 2. The hollow triangle in Figure 1 represents its present inclination angle and age. The hollow triangles in Figure 2 are the periods and period derivatives at ages of 10 yr, 100 yr, $10^3$ yr, $10^4$ yr, $10^5$ yr, $10^6$ yr, and $10^7$ yr, respectively. The death period and death age are about 28 s and $1.4 \times 10^5$ yr, respectively.

As we can see from Figure 1, the inclination angle decreases as the pulsar ages, which means that the magnetic axis and the rotational axis tend to align. In the $P$–$P$ diagram (Figure 2), the pulsar first evolves to the right under the combined effect of particle winds and magneto-dipole radiation, and then turns down under the effect of pulsar “death.” It is possible to predict that PSR J0250+5854 should be an old high magnetic field pulsar or magnetar, which is on the death edge. As the magnetospheric particles are exhausted, its radio radiation will tend to stop. That may be why nulling pulses are observed (Zhang et al. 2007; Kou & Tong 2015). Besides, it may have a relatively small inclination angle due to the alignment of the rotational and magnetic axes (Philippov et al. 2014; Tong & Kou 2017). After the death point, the pulsar will only be spun-down by magneto-dipole radiation, and the effective magnetic field should be $B \sin \alpha$. From the calculation results, the magnetic field of PSR J0250+5854 is still high, of the order of $10^{14}$ G. Its true age is much smaller than its characteristic age. It is still possible to observe magnetar-like emissions (Perna & Pons 2011).

Besides, as we can see from evolution tracks in Figure 2, the rotational period increases slowly after the death point because of the decrease in spin-down torque. The period derivative at the death point is $P_{\text{death}} = 5 \times 10^{-16} (P_{\text{death}} / 1 \text{ s})^3 (V_{\text{gap}} / 10^{11} \text{ V})^2 \sin^2 \alpha$ (Contopoulos & Spitkovsky 2006; Tong & Xu 2012). For a pulsar with $B = 10^{14}$ G and $V_{\text{gap}} = 10^{13}$ V, its maximum inclination angle is $3^\circ 4$, and its expected period and period derivative are 8.8 s and $1.2 \times 10^{-15}$ s/s, respectively. We could hence predict that, for similar long-period pulsars, most of them should have a relatively small period derivative, i.e., $<10^{-15}$ s/s.

3. Rotational Evolution in the Case of Magnetic Field Decay

In this case, rotational evolution of the pulsar under the effect of magnetic field decay will be discussed. We also take the same assumption with $k_0 \approx k_1 \approx 1$ in the spin-down torque, and pulsar rotational evolution should be (Spitkovsky 2006)

$$I \ddot{\Omega} = \frac{2 R_6}{c^3} \Omega^3 (\sin^2 \alpha + 1) = -\frac{B^3 R_6^3}{4 c^3} \Omega^3 (\sin^2 \alpha + 1). \quad (8)$$

Because magnetars are generally taken to be powered by a high magnetic field, magnetic field decay is naturally and widely discussed (Goldreich & Reisenegger 1992; Heyl & Kulkarni 1998; Viganò et al. 2013; Igoshov & Popov 2018). For an isolated neutron star, numerical calculations of magnetic field decay can generally expressed in a simple power law with decay index $\beta = \frac{d B}{d t} \propto -B^{1+\beta}$ (Colpi et al. 2000; Dall’Osso et al. 2012). The resulting changes are only quantitative for different forms of magnetic field decay. The magnetic energy may be dissipated by Hall/ohmic diffusion in the stellar crust, and an analytical decay could be expressed as (Aguilera et al. 2008; Popov & Turolla 2012)

$$B(t) = \frac{B_0 \exp(-t/\tau_0)}{1 + (\tau_0/\tau_H)[1 - \exp(-t/\tau_0)]} + B_{\text{fin}}, \quad (9)$$

where $B_0$ is the initial field, $B_{\text{fin}}$ is the relic field, and $\tau_0$ and $\tau_H$ are the characteristic timescale of ohmic and Hall decay, respectively.

3.1. Spin Down of PSR J0250+5854

Assuming an initial magnetic field of $B_0 = 4 \times 10^{15}$ G, together with $\tau_0 = 10^6$ yr, $\tau_H = 10^3$ yr, and $B_{\text{fin}} = 8 \times 10^{12}$ G, the magnetic field evolution can be calculated from Equation (9),

\[ 10 \]

which is shown in Figure 3.
Given a typical inclination angle of $45^\circ$, together with an initial period of 0.01 s, the rotational evolution of PSR J0250 +5854 could be calculated from Equations (8) and (9), which is shown in Figure 4. The solid triangles represent its periods and period derivatives at ages of 10 yr, 100 yr, 10$^2$ yr, 10$^3$ yr, 10$^4$ yr, 10$^5$ yr, 10$^6$ yr and 10$^7$ yr, respectively. The age and present magnetic field are about $1.4 \times 10^5$ G and $3.4 \times 10^3$ G, respectively. As we can see from Figure 3, the magnetic field decays sharply at ages between $10^5$ yr and $10^6$ yr, which will result in a decrease in the spin-down torque. Correspondingly, the rotational evolution line quickly turns down after age about $10^5$ yr. As shown in Figure 4, the evolution line passes through the region of SGR 1806-20, a so-called high magnetic field magnetar with dipole-magnetic field about $4 \times 10^{15}$ G at the pole (which is chosen as the initial magnetic field). It is possible to predict that the precursor of PSR J0250+5854 is a magnetar. Due to the decay of magnetic field, the magnetic-field-powered magnetospheric activity will become weaker and tend to stop. From the calculation results, it may be hard to observe magnetar-like burst (Perna & Pons 2011).

As the magnetic field tends to a constant value after $10^6$ yr, the pulsar will spin down under a constant spin-down torque, and $\dot{P} = 4.0 \times 10^{-14}/P$ in the case of $\alpha = 45^\circ$, according to Equation (8). In this case, for similar long-period pulsars, most of them should have relatively higher period derivatives, i.e., $\sim 10^{-15}$ s/s.

Several cases could be computed by varying the initial magnetic field, $B_0$; the Hall timescale, $\tau_H$; as well as the inclination angle, $\alpha$. The evolution tracks are roughly the same, and the results only change quantitatively. The aim of this section is to probe the possible evolution path of the long-period pulsar under the existing parameter space. Hence, a relatively high initial magnetic field is chosen here.

4. Discussions

The pulsar will evolve along isodynamic lines under the pure magneto-dipole radiation model. It is hard to explain observations of the pulsar with such a hypothesis. There should not be period clustering among pulsars in this case. However, it would be different when considering physical braking torque. Colpi et al. (2000) discussed the period clustering of the anomalous X-ray pulsars by considering coupled evolution of the thermal and magnetic field. The pulsar clustering could also be identified under the two spin-down models discussed in this paper and in terms of the period derivative.

The pulsar death line is defined as a threshold when pair production ceases, and it is model dependent (Ruderman & Sutherland 1975; Chen & Ruderman 1993; Zhang et al. 2000; Zhou et al. 2017). For a specific pulsar, its death depends on its magnetic field and the potential drop of the acceleration gap (Equation (6)). Therefore, it is not strange to find pulsars under the death lines or outside the death valley. As discussed in Kou & Tong (2015), the particle density may decrease as pulsars spin down. Hence, for pulsars on the death edge, their radio emissions tend to stop, and they may be observed in abnormal ways, such as nulling, intermittent pulsar, or ever rotational radio transients (Zhang et al. 2007; Karako-Argaman et al. 2015).

The evolution of the inclination angle is also widely studied; statistical studies show that long-period pulsars have relatively small inclination angles (Lyne & Manchester 1988; Tauris & Manchester 1998). The same conclusion is performed by a statistical study of the pulse width of radio pulsars with interpulse emission (Maciesiak & Gil 2011). In a 3D magnetosphere, the magnetosphere may also generate a torque to align the rotational axis and magnetic axis. In other words, the inclination angle tends to decrease (Phillippov et al. 2014; Tong & Kou 2017). Tong & Xu (2012) applied the spin-down model of Contopoulos & Spitkovsky (2006) to simulate the rotational evolution of SGR 0418+5729, which is a so-called low magnetic field magnetar. They pointed out that SGR 0418+5729 may be a normal magnetar but with a small inclination angle. From the point of view of inclination angle evolution, this is possible. PSRs J1119–6127 and PSR J1846–0258 are two young pulsars with high magnetic fields about $8 \times 10^{13}$ G and $9.7 \times 10^{13}$ G at the pole. Both of them are observed with magnetar-like bursts (Gavriil et al. 2008; Göğüş et al. 2016).
Besides, the radio emission of PSR J1119–6127 disappeared during the bursts, but reappeared about two weeks after the bursts (Majid et al. 2017). Connections between high magnetic field pulsars and magnetars are discussed (Archibald et al. 2017). The wind braking model is applied to explain their observations and to simulate their long-term rotational evolution (Ou et al. 2016). From the point of view of magnetosphere evolution, PSR J0250+5854 may be a high magnetic field pulsar or a magnetar on the death edge; it has a small inclination angle but a strong magnetic field. Its true age may be much smaller than the characteristic age. Due to its relatively high magnetic field, it may be burst active but with a relatively longer waiting time (Perna & Pons 2011).

The Hall and ohmic diffusion are both temperature dependent, the magnetothermoelectric is studied (Pons et al. 2009; Viganò et al. 2013). For PSR J0250+5854, an age of $1.4 \times 10^7$ yr is calculated with an initial magnetic field of $4 \times 10^{12}$ G. The expected thermal luminosity of PSR J0250+5854 is about $10^{30}$ erg s$^{-1}$ via the magnetothermoelectric models of Viganò et al. (2013). However, the Swift/X-Ray Telescope nondetection places an upper limit on the luminosity of $1.5 \times 10^{32}$ erg s$^{-1}$ on $\dot{E}_f = 85$ eV for $N_f = 9 \times 10^{23}$ cm$^{-2}$ (Tan et al. 2018). One possibility is that the evolution of PSR J0250+5854 is dominated by magnetospheric evolution. However, because the inner super-dense matter of neutron star is still a mystery, it is also possible that PSR J0250+5854 has undergone a rapid cooling process (Yakovlev et al. 2008).

In fact, both the effet of magnetospheric evolution and magnetic field decay may work on the pulsar; the dominant mechanism could also be identified by the period derivative and the distributions of long-period pulsars. In the case of magnetospheric evolution, the spin-down torque continues to decrease in the later stage, which will result in a continuous decrease in the period derivative (Figure 2). Hence, a relatively low period derivative will be measured—for example, the radio pulsar PSR J2144–3933, with a period of 8.5 s and a relatively low period derivative of $4.96 \times 10^{-16}$ s/s (Young et al. 1999). However, in the case of magnetic field decay, the magnetic field tends to be constant at its late stage, and so does the spin-down torque. Pulsars will have a relatively high period derivative in this case. Clustered distribution of more similar long-period pulsars will help to distinguish these two cases.

A fallback disk model is also commonly applied to explain the observations of pulsars and pulsar-like objects. Due to the significant increase in the period during the propeller phase, the evolution of a long-period neutron star could be understood by considering fallback disk torque (Menou et al. 2001; Fu & Li 2013; Tong et al. 2016). After the propeller phase, the neutron star tends to be in rotational equilibrium with the fallback disk at the equilibrium period of $P_{eq} = 2\pi \left(\frac{8\pi}{GM}\right)^{1/2}$, where $G$ is the gravitational constant and $M$ is the mass of the neutron star.

We also calculated the possible evolution of PSR J0250+5854 under the fallback disk model of Tong et al. (2016). Assuming that PSR J0250+5854 is spinning at the rotational equilibrium phase, a relatively large age about $10^7$ yr could be estimated according to its period derivative: $\dot{P} \approx \frac{3\alpha}{\alpha M}$, where $\alpha$ is the power-law index of the mass accretion rate, and $\alpha \approx 1.25$ is taken here. The model implies that the magnetic field of PSR J0250+5854 is about $10^{12}$ G, which is much smaller than its dipole-magnetic field. Similarly, a lower magnetic field of about $10^{11}$ G and a larger age of about $10^8$ yr are expected for PSR J2144–3933, because of its low period derivative. However, the typical lifetime of a fallback disk is generally taken as about a few thousand years (Menou et al. 2001). The model-expected period derivatives would be much larger than the observed values for these two long-period pulsars. One possibility is that the fallback disk around them is not active, and the pulsar is braked by magnetic dipole radiation at the moment; their ages and magnetic fields are much closer to their characteristic ages and characteristic magnetic fields. The pulsar will spin down along the isodynamic lines. Future measurements of the pulsar age and magnetic field would help to probe the possibility of braking under torques due to a fallback disk for these long-period pulsars.

In conclusion, PSR J0250+5854 may be an old, high magnetic field pulsar or a magnetar. Considering the magnetospheric evolution, PSR J0250+5854 may be on the death edge, it may have a small inclination angle and a relatively high magnetic field, and magnetar-like emissions may be observed. However, in the case of magnetic field decay, the magnet-field-powered magnetar-like emission may be difficult to observe. Besides, from the point of view of evolution studied, pulsars will have low period derivatives in the case of magnetospheric evolution but have relatively higher period derivatives in the case of magnetic field decay. Clustering distribution of more similar long-period pulsars will also help to distinguish these two cases.

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