Is the Birth of PSR J0538+2817 Accompanied by a Gamma-ray Burst?

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ABSTRACT

Recently, the Five-hundred-meter Aperture Spherical radio Telescope (FAST) measured the three-dimensional velocity of PSR J0538+2817 with respect to its associated supernova remnant S147 and found a possible spin-velocity alignment for this pulsar. Here we show that the high velocity and the spin-velocity alignment of this pulsar can be explained by the so-called electromagnetic rocket mechanism. In this framework, the pulsar is kicked in the direction of the spin axis, which naturally explains the spin-velocity alignment. We scrutinize the evolution of the pulsar and show that the kick process can create a highly relativistic jet at the opposite direction of the kick velocity. The lifetime and energetics of the jet is estimated. It is argued that the jet can generate a gamma-ray burst (GRB). The long term dynamical evolution of the jet is calculated. It is found that the shock radius of the jet should expand to about 32 pc at present, which is well consistent with the observed radius of the supernova remnant S147 (32.1 ± 4.8 pc). Additionally, our calculations indicate that the current velocity of the GRB remnant should be about 440 km s⁻¹, which is also roughly consistent with the observed blast wave velocity of the remnant of S147 (500 km s⁻¹).

Key words: gamma-ray bursts – stars: neutron – pulsars: general – stars: magnetars

1 INTRODUCTION

It is well known that many pulsars possess large velocities compared with main sequence stars. Previous statistical study of young pulsars has shown an average three-dimensional (3D) velocity of about 400 km s⁻¹ at birth (Hobbs et al. 2005). Some of the fastest ones can even reach ~1000 km s⁻¹. The origin of the high-velocity pulsars is still under debate. A natural requirement is some kind of asymmetry during the supernova (SN) explosion that creates a kick to the pulsar. It has been suggested that an anisotropic mass ejection or neutrino ejection could be responsible for the pulsar kick (Sagert & Schaffner-Bielich 2008; Janka 2017). Meanwhile, the electromagnetic rocket mechanism is also a promising model to explain the high-velocity pulsars (Harrison & Tademaru 1975; Lai et al. 2001; Huang et al. 2003). In this framework, the young pulsar is supposed to have an off-centered dipolar magnetic field. The asymmetry in the magnetic field will lead to extra radiation in the direction of the spin axis and give the pulsar a recoil velocity. The electromagnetic rocket process may last for a relatively long time (Janka 2021). However, the timescale could also be as short as ~50 s if the pulsar has a large magnetic field and a small initial period, namely a millisecond magnetar (Huang et al. 2003).

Recently, Yao et al. (2021) reported the evidence for 3D spin-velocity alignment of PSR J0538+2817. They adopted a scintillation method to get the radial velocity of this pulsar by using observations made with the Five-hundred-meter Aperture Spherical Radio Telescope (FAST). Combining the pulsar observations of Chatterjee et al. (2009), they derived the inclination angle between the 3D pulsar velocity and the line of sight as $\zeta = 110°^{+16°}_{−5°}$ and the overall 3D speed as $407^{+79}_{−27}$ km s⁻¹. Using the polarization fitting method, they further obtained the inclination angle of the pulsar spin axis with respect to the line of sight as $\zeta_{\text{pol}} = 118°.5 ± 6.3°$. They argued that PSR J0538+2817 is the first pulsar that directly shows a 3D spin-velocity alignment. It is worth noting that the spin-velocity alignment has previously been hinted in the Crab and Vela pulsars, but observations only limit their alignments in the two-dimensional (2D) plane (Lai et al. 2001; Johnston et al. 2005).

The 3D spin-velocity alignment is not easy to be explained by current simulations of supernova explosions which mainly focus on anisotropic mass ejection or neutrino ejection (Janka 2017; Müller et al. 2019). Recently, Janka et al. (2021) described a subtle scenario to explain the alignment, considering the asymmetric mass ejection in the supernova explosion. In all previous hydro-dynamical supernova simulations, the effect of accretion by the neutron star is generally omitted. In their new scenario, the newly-born neutron star obtains a high-velocity through the anisotropic supernova explosion in the first few seconds and runs away from the explosion center. Then the spin direction of this neutron star would later be affected by the fallback materials mainly from the direction of neutron star motion, which may potentially lead to some kinds of spin-velocity alignment. However, even in their simulations, a satisfactory alignment could be obtained only in some rare cases. On the other hand, we note that the spin-velocity alignment is a natural result in the framework of the electromagnetic rocket scenario (Harrison & Tademaru 1975). Thus we will mainly focus on this mechanism in our study.

Gamma-ray Bursts (GRBs) are explosions with an extremely high...
energy release. It is generally believed that long GRBs lasting for tens of seconds are associated with core collapse of massive stars (Woosley 1993; Iwamoto et al. 1998). Meanwhile, short GRBs lasting for less than ~2 s are deemed to be related to the mergers of two compact stars (Eichler et al. 1989; Abbott et al. 2017). In the former scenario, the core collapse of massive stars often leaves a remnant of a black hole or a millisecond magnetar to act as the central engine of GRBs. However, as suggested by Dar & Plaga (1999), GRBs might also come from pulsar kicks. This model interestingly connects high-speed pulsars with GRBs. Later, Huang et al. (2003) examined the kick process and studied the properties of the resultant GRBs in details. Here, we go further to argue that the observed spin-velocity alignment of PSR J0538+2817 indicates that the birth of this pulsar may be associated with a long GRB.

This paper is organized as follows. In Section 2, we briefly introduce the observed features of PSR J0538+2817 and its associated supernova remnant (SNR) S147. Section 3 describes the GRB model in detail. We calculate the dynamics and compare our results with the observational data in Section 4. The possible decay of the magnetic field and the spin evolution of the pulsar is studied in Section 5. Finally, our conclusions and brief discussion are presented in Section 6.

2 PSR J0538+2817 AND S147

PSR J0538+2817 was first discovered by Anderson et al. (1996) with the Arecibo radio telescope. This pulsar is thought to be associated with SNR S147. It has a short period of 143.16 ms with a period derivative of 3.67 × 10^{-15} s s^{-1} (Anderson et al. 1996; Kramer et al. 2003). Considering a simple magnetic dipole radiation, its characteristic age should be approximately 600 kyr. As for the distance, both parallax distance and the dispersion measure (DM) distance suggest that it is about 1.3 kpc away from us (Kramer et al. 2003; Chatterjee et al. 2009). The proper motion precisely measured by the Very Long Baseline Array (VLBA) of \( \mu_\alpha = -23.57 \pm 0.1 \text{ mas yr}^{-1} \) and \( \mu_\delta = 52.87 \pm 0.1 \text{ mas yr}^{-1} \) suggests a transverse velocity of \( 357_{-43}^{+59} \text{ km s}^{-1} \) (Chatterjee et al. 2009). After converting it to the local standard of rest (LSR), the proper motion becomes \( \mu_\alpha = -24.4 \pm 0.1 \text{ mas yr}^{-1} \) and \( \mu_\delta = 57.2 \pm 0.1 \text{ mas yr}^{-1} \) (Dinçel et al. 2015). Then, assuming a distance of 1.33 ± 0.19 kpc, the transverse velocity in the LSR is \( 391 \pm 56 \text{ km s}^{-1} \) (Yao et al. 2021). From the transverse velocity and the conjecture of its association with S147, its kinematic age can be derived as 34.8 ± 0.4 kyr (Yao et al. 2021). We summarize the observed and derived parameters of PSR J0538+2817 in Table 1 for reference.

The kinematic age derived above is very different from the characteristic age of PSR J0538+2817. It indicates that the characteristic age may have been overestimated. Such an overestimation is not rare for pulsars and it may be caused by a variety of factors. For example, the magnetic field of pulsars may vary or decay on a long timescale (Guseinov et al. 2004). Another possibility is that the pulsar may have a large initial period. However, in the case of PSR J0538+2817, the initial period should be as long as \( R_0 = 139 \text{ ms} \) to make the two ages compatible (Kramer et al. 2003). Such a long initial period is rare for young pulsars. In fact, it is widely believed that pulsars should be born with a millisecond initial period. In this study, we argue that PSR J0538+2817 should be a millisecond magnetar at birth. It will be shown below that the observed high speed and the spin-velocity alignment can all be naturally explained in this circumstance. The inconsistency between the kinematic age and the characteristic age is then attributed to a significant decay of the dipolar magnetic field due to fallback accretion, which will be discussed in detail in Section 5.

As for the SNR of S147, although an early estimation gave a large age of about 100 kyr (Kirshner & Arnold 1979), it is often thought to have a smaller age of about 30 kyr, similar to the kinematic age of PSR J0538+2817 (Katsuta et al. 2012). Despite of its old age, this SNR still shows long delicate filaments in optical band with a nearly spherical shape (Dinçel et al. 2015). However, other than considering it as a perfect spherical shape, some authors argued that there exists an “ear” morphology in this SNR (Grichener & Soker 2017; Bear & Soker 2018), but note that the “ear” is not right on the opposite direction of the pulsar velocity (Bear & Soker 2018; Soker 2021). More interestingly, from the Hα image of S147 presented by Gvaramadze (2006), the filamentary structure seems to be more concentrated in the south-east, opposite to the direction of the pulsar proper motion. The distance of this remnant is estimated to be approximately 1.3 kpc, consistent with that of PSR J0538+2817 (Dinçel et al. 2015; Yao et al. 2021). Sofue et al. (1980) presented a 5 GHz map of S147 and measured its angular radius as \( \theta_\alpha = 83^\circ \pm 3^\circ \), which corresponds to a size of \( R_\alpha = 32.1 \pm 4.8 \text{ pc} \) at a distance of \( 1.33 \pm 0.19 \text{ kpc} \) (Yao et al. 2021).

The possible spin-velocity alignment of PSR J0538+2817 was previously proposed by Romani & Ng (2003). With the help of Chandra X-ray Observatory (CXO) imaging, they found that this pulsar might be surrounded by a faint pulsar wind nebula (PWN). Assuming that the elongated structure is an equatorial torus, they argued that the pulsar spin and velocity are aligned. This alignment was later supported by several other papers (Ng et al. 2007; Johnston et al. 2007), but only in the 2-dimensional plane. Recently, Yao et al. (2021) confirmed this alignment in the 3D space. They analyzed the scintillation arcs of PSR J0538+2817 based on the dynamic spectra obtained with FAST. Assuming that this pulsar is associated with S147 and that S147 has a spherical structure, they speculated that the pulsar-scattering screen is located at the SNR shell and determined the location of this pulsar in the 3D space. Then, considering the pulsar’s kinematic age, they derived the 3D velocity of the pulsar as \( 407_{-57}^{+79} \text{ km s}^{-1} \) and the corresponding 3D inclination angle as \( \zeta = 110^\circ_{-25}^{+15} \). Also, they fitted the FAST polarization data with the rotating vector model (RVM) (Johnston et al. 2005) and got the inclination angle of the spin axis with respect to the line of sight as \( \zeta_{\text{pol}} = 118^\circ_{-5}^{+6} \). These data strongly support the idea that the spin and velocity of PSR J0538+2817 are aligned.

3 GRB CONNECTED WITH THE BIRTH OF PSR J0538+2817

We argue that PSR J0538+2817 is born as a millisecond magnetar. At its birth, the electromagnetic rocket mechanism can satisfactorily explain the high kick speed and the spin-velocity alignment. In this framework, the kick of the pulsar should be accompanied by a relativistic jet moving in the opposite direction of the pulsar velocity. The jet will possess enough energy to power a long GRB. A schematic illustration of our scenario is shown in Figure 1. Here we describe the scenario in detail and confront our model with the various observational data.

3.1 Kick velocity and kick timescale

A pulsar with an off-centered dipolar magnetic field will lose energy asymmetrically, which would in return exert a recoil force on the pulsar (Harrison & Tademaru 1975). The force is parallel to the
Figure 1. Schematic illustration of our scenario. The pulsar is born as a millisecond magnetar and gains a large kick velocity through the electromagnetic rocket process which lasts for approximately 180 s. Meanwhile, a highly beamed ultra-relativistic outflow is launched opposite to the kick direction, which will be powerful enough to generate a GRB. After producing the GRB, the jet continues to move outward, expanding laterally at the same time. After about 34.8 kyr, the radius of the jet increases to \(32 \text{pc}\), which is consistent with the observed radius of SNR S147 (32.1 ± 4.8 pc).

Table 1. Parameters of PSR J0538+2817

| Observed parameters | Value | Ref. | Derived parameters | Value | Ref. |
|---------------------|-------|------|--------------------|-------|------|
| R.A. (J2000)        | 05\(^{h}\) 38\(^{m}\) 25\(^{s}\).0623 | 2 | Characteristic age (kyr) | 600 | 4 |
| Dec. (J2000)        | 28° 17′ 09″.1 | 2 | Kinematic age (kyr) | 34.8 ± 0.4 | 4 |
| Period, \(P\) (ms) | 143.157776645(2) | 1 | DM distance, \(D_{\text{DM}}\) (kpc) | 1.2 | 3 |
| First derivative, \(P\) (×10\(^{-15}\)) | 3.6681(1) | 1 | Parallax distance, \(D_{\text{P}}\) (kpc) | 1.30 ± 0.22 | 3 |
| Dispersion measure (pc cm\(^{-6}\)) | 39.57 | 3 | Transverse velocity, \(V_{\perp}\) (km s\(^{-1}\)) | 357 ± 59 | 3 |
| \(\mu_{\alpha}\) (mas yr\(^{-1}\)) | \(-23.57 ± 0.10\) | 3 | 3D velocity, \(V_{3D}\) (km s\(^{-1}\)) | 407 ± 57 | 4 |
| \(\mu_{\delta}\) (mas yr\(^{-1}\)) | \(52.87 ± 0.10\) | 3 | Magnetic field (G) | 7 × 10\(^{11}\) | 1 |
| \(\pi\) (mas) | \(0.72 ± 0.12\) | 3 | Spin-down luminosity (erg s\(^{-1}\)) | \(5 × 10^{34}\) | 1 |

\(^a\) List of references: 1 - Anderson et al. (1996); 2 - Kramer et al. (2003); 3 - Chatterjee et al. (2009); 4 - Yao et al. (2021)

is somewhat similar to Equation 4 of Lai et al. (2001), but note the slight difference in the adopted configuration of the magnetic field.

Here, we consider a neutron star with a typical mass and radius of \(M_{\text{NS}} = 1.4M_{\odot}, R_{\text{NS}} = 12\) km (Most et al. 2018; Abbott et al. 2018; Miller et al. 2019). Meanwhile, the spin period of the newborn neutron star is taken as \(P_0 = 1\) ms, which can be easily acquired after the contraction of the original proto-neutron star (Wheeler et al. 2000). As for the displacement of the dipole with respect to the rotation axis, Lai et al. (2001) assumed a distance of \(s = 10\) km for their neutron star with radius of 10 km. In this study, we consider a more moderate value of \(s = 7\) km. Under our configuration, the natal kick velocity can be larger than \(\sim 400\) km s\(^{-1}\) as shown in Equation 1.

During the kick process, the pulsar will lose energy and will correspondingly spin down (Harrison & Tademaru 1975). As a result, its spin period will evolve with time as

\[
P(t) \approx P_0 \left[ 2 \times 10^{-2} s^{-1} \left( \frac{P_0}{1\ \text{ms}} \right)^{-2} \left( \frac{R_{\text{NS}}}{12\ \text{km}} \right)^{2} \left( \frac{\mu_{\alpha}/\mu_{\delta}}{1.5} \right)^{-2} \times \left( \frac{B_0}{7 \times 10^{15} \text{ G}} \right)^{2} t + 1 \right]^{\frac{1}{2}},
\]

where \(B_0\) is the surface magnetic field of the pulsar. Here we take the magnetic field as several times 10\(^{15}\) G in our modeling, which is quite typical for a newborn millisecond neutron star to act as the central engine of GRB (Wheeler et al. 2000; Metzger et al. 2011; Janka 2012; Kumar & Zhang 2015).

From Equations 1 and 2, we see that the velocity acquired by the pulsar is a function of \(t\). Taking \(V_{\text{kick}} \sim 400\) km s\(^{-1}\) as a target speed, we find that the kick process will last for a timescale of \(\tau \sim 180\) s. After the kick process, the spin period decreases to \(P_1 = 2.15\) ms according to Equation 2.

3.2 Energetics of the GRB

Accompanying the kick, a jet will be launched due to the momentum conservation. The momentum of the jet can be calculated as \(P_{\text{flow}} = M_{\text{NS}} V_{\text{kick}}\). In the electromagnetic rocket mechanism, very few baryons will be included in the jet, so that the outflow should be highly relativistic. Taking \(V_{\text{kick}} \sim 400\) km s\(^{-1}\), the total energy of the relativistic jet (\(E_{\text{flow}}\)) can be derived as (Dar & Plaga 1999; Huang et al. 2003)

\[
E_{\text{flow}} = P_{\text{flow}} c = 3.3 \times 10^{51} \text{ erg}
\]

where \(c\) is the speed of light. Note that this pulsar is a millisecond magnetar at birth and the total energy of the jet should be smaller...
than the initial spin energy of the magnetar. Considering a typical moment of inertia of $I = 10^{45}$ g cm$^2$, the spin energy is

$$E_{\text{spin}} = \frac{1}{2} I \left( \frac{2p}{P_0} \right)^2 \approx 2 \times 10^{52} \left( \frac{I}{10^{45} \text{ g cm}^2} \right) \left( \frac{P_0}{1 \text{ ms}} \right)^{-2} \text{ erg}. \quad (4)$$

From the calculations in the above subsection, we get the terminal spin period after the kick process as $P = 2.15$ ms. It corresponds to a spin energy of $E_{\text{spin}} = 4.3 \times 10^{51}$ erg. Therefore, the spin energy loss is $\sim 1.57 \times 10^{52}$ erg. We see that this energy is large enough to energize the jet, thus the above kick process is basically self-consistent.

If observed on-axis, the jet will show up as a GRB. Usually only a portion of the kinetic energy will be emitted as $\gamma$-rays during the main burst phase. Designating the efficiency of $\gamma$-ray emission as $\varepsilon$ and the half opening angle of the jet as $\theta$, then the isotropic energy of the GRB is

$$E_{\text{iso}} = \frac{2\varepsilon E_{\text{flow}}}{1 - \cos \theta} \approx 4\varepsilon M_{\text{NS}}V_{\text{NS}}c^2\theta^{-2} = 1.3 \times 10^{53} \text{ erg} \times (\frac{\varepsilon}{0.1}) (\frac{\theta}{0.1})^{-2} (\frac{M_{\text{NS}}}{1.4 M_\odot}) (\frac{V_{\text{NS}}}{400 \text{ km s}^{-1}}). \quad (5)$$

We see that for typical parameters of $\varepsilon = 0.1$ and $\theta = 0.1$, the isotropic energy of the GRB can be as high as $\sim 10^{53}$ erg. In our scenario, since the kick process lasts for $\tau \sim 180$ s, the GRB should correspondingly be a long one.

## 4 DYNAMICS OF THE REMNANT

The kick process and the accompanying GRB occurred about 34.8 kyr ago. After producing the $\gamma$-ray burst, the jet interacted with the circum-burst interstellar medium and got decelerated. It would expand laterally as well. Now we calculate the long-term dynamical evolution of the outflow and compare the results with the observational data of the remnant S147.

The dynamical evolution of relativistic outflows that produce GRBs has been extensively studied by many authors. Following the generic dynamical equation proposed by Huang et al. (1999), many other authors have studied some subtle effects such as the role played by the pressure of the shocked material (van Eerten et al. 2010; Pe'er 2012). Xu & Huang (2010) investigated the evolution of a ring-shaped jet. Lamb et al. (2018) studied the jet-cocoon interaction. Geng et al. (2013, 2016) discussed the effect of a delayed energy injection. Zouaoui & Mebarik (2019) examined the compatibility of the generic dynamical equation with the Sedov solution in the nonrelativistic phase. Jets propagating through a density-jump medium (Geng et al. 2014) or a stratified circumstellar medium (Fraija et al. 2021) are also studied in detail. Very recently, magnetized GRB shocks have been further discussed by Chen & Liu (2021).

The case studied here is relatively simple. We only need to consider an adiabatic jet interacting with a homogeneous interstellar medium (ISM). Following Huang et al., the dynamics of the jet can be described by the following four equations (Huang et al. 1999, 2000a,b).

$$\frac{dR}{dt} = \beta c \gamma (\gamma + \sqrt{\gamma^2 - 1}), \quad (6)$$

$$\frac{dm}{dR} = 2\pi R^2 (1 - \cos \theta) n m p, \quad (7)$$

$$\frac{d\theta}{dt} = \frac{c_s (\gamma + \sqrt{\gamma^2 - 1})}{R}, \quad (8)$$

$$\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M_{ej} + \epsilon_s m + 2(1 - \epsilon_s) \gamma m}. \quad (9)$$

Here, $R$ is the radius of the shock in the GRB rest frame, $m$ is the swept-up ISM mass, $\gamma$ is the Lorentz factor of the outflow and $\beta = \sqrt{\gamma^2 - 1}/\gamma$ is the observer’s time, $n$ is the number density of the surrounding ISM, $m_p$ is the proton mass, $c_s$ is the comoving sound speed, and $\epsilon_s$ is the radiative efficiency.

We have calculated the long-term evolution of the jet numerically. The relevant parameters are taken as follows. Following our model described in Section 3, the total energy of the jet is $E_{\text{flow}} = 3.3 \times 10^{51}$ erg. The mass of ejecta is set as $M_{ej} = 1.2 \times 10^{-6} M_\odot$, so that the initial Lorentz factor takes a typical value of $\gamma_0 = 150$ ($E_{\text{flow}} = \gamma_0 M_{ej} c^2$). The initial half opening angle of the jet is assumed as $\theta_0 = 0.1$. Considering that S147 is in a low-density area (Katsuta et al. 2012), we take the number density as $n = 0.1$ cm$^{-3}$. The numerical result for the evolution of the shock radius is shown in Figure 2.

We find that the shock radius of the jet is about 32.04 pc at present, which agrees well with the measured radius of S147 (32.1 ± 4.8 pc, at a distance of 1.33 kpc). Figure 3 illustrates the evolution of the shock velocity. S147 is currently in the Sedov-Taylor phase. Katsuta et al. (2012) have estimated its blast wave velocity as 500 km s$^{-1}$. As shown in Figure 3, our result indicates an expansion velocity of about 440 km s$^{-1}$ for the remnant today. It is also well consistent with the estimation made by Katsuta et al. (2012). In Figure 4, we plot the evolution of the half opening angle of the jet. We see that the outflow is expected to expand to an angle of 2.67 rad currently. It means that the jet has been be widely diffused after propagating for a long time.

A supernova, when associated with a GRB, could be very energetic and is usually called a hypernova. Some of the most powerful hypernovae can even have an isotropic energy up to $10^{52}$ erg (Preece et al. 2018). Interestingly, the kinetic energy of the remnant associated with PSR J0538+2817 (i.e. SNR S147), has been estimated as $(1-3) \times 10^{51}$ erg (Katsuta et al. 2012). We argue that the remnant should actually be a mixture of the supernova remnant and the highly diffused GRB jet. According to our modeling, the GRB jet initially had an intrinsic kinetic energy of $3.3 \times 10^{51}$ erg (see Equation 3). In the prompt GRB phase, it might lose a significant portion of its energy (typically $\sim 10\% - 50\%$). Then, in the early afterglow stage (being highly radiative), it would further lose some energy due to radiation loss. When it finally became adiabatic, the kinetic energy is expected to be comparable to that of the isotropic supernova remnant. From Figure 4, we see that the jet has expanded to an angle of 2.67 rad today ($t = 34.8$ kyr). On the other hand, although the supernova remnant itself (which is non-relativistic) was initially much slower and was left behind, it would finally catch up with the GRB remnant because it was much more massive and thus decelerated more slowly. As a result, SNR S147 should in fact be a mixture of the supernova remnant and the GRB outflow. Since the GRB outflow has expanded to a wide range of $\theta = 2.67$, the mixing of the two components should be complete so that the original GRB jet could no longer be discerned. Anyway, it is interesting to note that the southeastern portion of SNR S147, which is opposite to the direction of the pulsar motion, is obviously brighter than the northwest section. It clearly supports the existence of a one-sided jet.

## 5 MAGNETIC FIELD DECAY AND PERIOD EVOLUTION

In our scenario, the initial magnetic field strength of the pulsar is $B_0 = 7 \times 10^{15}$ G. However, the current surface field inferred from the period derivative is around $7 \times 10^{11}$ G. It indicates that PSR J0538+2817 may have experienced a significant magnetic field decay.
Magnetic field decay has been frequently inferred from pulsar observations. A possible recent example is the famous binary neutron star merger event of GW170817. Most people believe that the remnant should be a short-lived neutron star that collapsed into a black hole in a few seconds (Shibata et al. 2017; Margalit & Metzger 2017; Ruiz et al. 2018). However, Yu et al. (2018) argued that the remnant could be a long-lived massive neutron star (Yu et al. 2018). According to their estimates, the remnant neutron star should have an initial surface magnetic field of $10^{14} - 10^{15}$ G. But constraints from the data of later kilonova observations suggest that the field was only in a range of $10^{11} - 10^{12}$ G several thousands of seconds after the gravitational wave event. Some unknown mechanisms thus might have acted to significantly reduce the magnetic field (Yu et al. 2018).

How the magnetic field of neutron stars decays is still under debate. For isolated pulsars, maybe the most probable mechanism should involve Ohmic dissipation or Hall drift (Pons & Geppert 2007). However, this is not an effective process and the dissipation timescale is usually as long as $\sim 10^3 - 10^6$ yr (Pons & Geppert 2007). Another possibility is that the pulsar accretes mass which buries the magnetic field to make it decrease (Fu & Li 2013; Yu et al. 2018). The accreted mass can either be from a companion star or from the fallback materials.

Here, for PSR J0538+2817, we adopt the latter mechanism and consider the fallback accretion. An empirical relationship between the magnetic field and the accreted mass ($\Delta M$) can be written as (Shibazaki et al. 1989; Fu & Li 2013),

$$B = \frac{B_0}{1 + \Delta M / 10^{-5} M_\odot},$$  \hspace{1cm} (10)

where $B_0$ is the initial magnetic field. For the magnetic field to decrease from $B_0 = 7 \times 10^{15}$ G to the currently observed value of $B = 7 \times 10^{11}$ G, the total accreted matter should be $\Delta M \sim 10^{-1} M_\odot$. Very recently, a detailed numerical simulation on the fallback accretion process has been conducted by Janka et al. (2021). It is revealed that a fallback mass of $\Delta M \sim 10^{-2} M_\odot$ is quite typical in the process (Janka et al. 2021). Additionally, the accretion timescale is generally in the range of $10^5 - 10^7$ s.

The decay of the magnetic field will have a significant influence on the spin-down of the pulsar. From the calculations in Section 3.1, we have argued that PSR J0538+2817 should have a small initial period of $P_0 \sim 1$ ms (see Equation 1). Then it experienced an electromagnetic kick process that lasted for about $\tau \sim 180$ s. After the kick process, the spin period decreased to about $P_1 = 2.15$ ms (see Equation 2). Later, the pulsar would spin down through normal dipolar emission mechanism. At this stage, if the pulsar had a constant magnetic field of $7 \times 10^{15}$ G, then the spin period would increase to about 370 ms in less than $1 \times 10^6$ s. However, as argued above, the magnetic field actually decayed significantly on a timescale of $\sim 10^3 - 10^5$ s due to the fallback accretion. Since the spin-down rate is proportional to the square of the surface magnetic field, the spin period will increase much slower. It would finally reach the observed period of 143 ms after 34.8 kyr. However, the detailed spin down process with a decreasing magnetic field is quite complicated and is beyond the scope of this study.

Figure 2. Long-term evolution of the shock radius after the jet produced the GRB. The observational data point represents the measured radius of S147 at present, which is 32.1 ± 4.8 pc (Yao et al. 2021). The calculated shock radius is 32.04 pc after 34.8 kyr, which is well consistent with the observations.

Figure 3. Long-term evolution of the shock velocity after the jet produced the GRB. The dashed lines mark the shock velocity at present, which is 440 km s$^{-1}$. It is consistent with the speed of $\sim 500$ km s$^{-1}$ estimated from observations by Katsuta et al. (2012).

Figure 4. Long-term evolution of the half opening angle of the jet. The dashed lines show the current half opening angle, which is 2.67 rad.
6 CONCLUSIONS AND DISCUSSION

An interesting spin-velocity alignment was recently reported for the high speed pulsar PSR J0538+2817 (Yao et al. 2021). We argue that this pulsar was initially born as a millisecond magnetar with a strong but asymmetrical magnetic field. The high kick speed and the spin-velocity alignment can be explained in the frame work of the electromagnetic rocket mechanism (Harrison & Tademaru 1975; Lai et al. 2001; Huang et al. 2003). It is suggested that the pulsar natal kick is accompanied by an ultra-relativistic jet in the opposite direction, which can essentially give birth to a long GRB. The long-term dynamical evolution of the jet is calculated. It is found that the shock radius of the jet should be 32.04 pc at present, which is well consistent with the observed radius of SNR S147 (32.1 ± 4.8 pc) (Yao et al. 2021). Our calculations indicate that the current shock velocity should be about 440 km s$^{-1}$. It also agrees well with the estimated speed of about 500 km s$^{-1}$ by Katsuta et al. (2012).

Gamma-ray bursts may occur in binary systems (Zou et al. 2021). It is interesting to note that an OB runaway star, i.e. HD 37424, has been identified by Dinçel et al. (2015) to be inside SNR S147. They argued that the OB star is an interacting binary companion of the progenitor of PSR J0538+2817. The OB star may affect the evolution of the progenitor and cause a small spin-velocity misalignment (5 − 10$^\circ$) due to the break-up of a pre-supernova binary system (Yao et al. 2021). However, it will have little impact on the relativistic jet in our model.

In our framework, an off-centered dipolar magnetic field is needed for PSR J0538+2817. Usually the magnetic field of pulsars is thought to be of a simple dipolar configuration which is not off-centered. However, note that the realistic situation might be much more complicated. For example, it has been suggested that the most rapidly rotating neutron stars may have more complex surface magnetic configuration (Ruderman et al. 1998). Meanwhile, recently Miller et al. (2019) studied PSR J0030+0451 and provided interesting constraints on its surface magnetic field from the hot spot observations. They used the observational data from the Neutron Star Interior Composition Explorer (NICER) and discerned three hot spots on the surface of the compact star. They argued that these hot spots strongly indicate that the pulsar has an offset dipolar magnetic field or even a multi-pole field. Therefore, for PSR J0538+2817, we believe that the existence of an off-centered magnetic field could not be expelled. In fact, the bulk magnetic field configuration of pulsars is closely connected with their internal structure. However, our knowledge about the interiors of neutron stars is still quite poor. For example, these so called “neutron stars” might even be strange quark stars (Geng et al. 2021). We hope that the unprecedented high accuracy observations of NICER on pulsars would help clarify the fascinating enigmas of neutron stars.

It has been shown that the kick process of PSR J0538+2817 might be accompanied by a GRB that happened in our own Galaxy about 34.8 kyr ago. The filamentary structure of SNR S147 seems to be more concentrated in the south-east, opposite to the kick direction. This may support our model, in which a jet producing the GRB was launched toward the opposite direction of the kick. However, it is not clear whether this GRB pointed toward us or not. If it did point toward us, it would impose a huge effect to the Earth. Interestingly, in a recent study, Wang et al. (2017) measured the $^{14}$C abundance of an ancient buried tree. They found rapid increases of $^{14}$C in the tree rings between BC 3372 and BC 3371. They suggested that it may be associated with the ancient supernova that create the Vela pulsar. The GRB considered here happened about 34.8 kyr ago and is ∼ 1.3 kpc away from us. It took about 4.2 kyr for the $\gamma$-rays to arrive at our planet. So, if the GRB pointed toward us, there may be some geological records on the Earth about 30,600 yr ago. Therefore, similar to Wang et al.’s case, we propose that people could also try to search for possible clues connected to the birth of PSR J0538+2817 through geological surveys.

Observationally, the GRB rate is only ∼ 0.2% of the SN rate (Woosley & Bloom 2006). Meanwhile, high-velocity neutron stars are quite common, and the average velocity of pulsars is about 400 km s$^{-1}$ at birth (Hobbs et al. 2005). One may worry that there would be too many GRBs according to our modeling. The contradiction can be relieved by considering the following requirements. First, not all high-speed pulsars are accompanied by an ultra-relativistic outflow. Some of them may acquire the high speed via other mechanisms. Second, the pulsar needs to be a millisecond one, together with a very strong magnetic field. Thirdly, even if the pulsar is accompanied by an ultra-relativistic outflow, the outflow may do not point toward us so that no GRB would be observed due to the beaming effect. Let us first consider normal bipolar jets with a half opening angle of 0.1 rad. Then the probability that these GRBs point toward us is only ∼ 0.5%. However, in our model, the jet is single-sided, so the fraction will further decrease by two fold to ∼ 0.25%. Synthesizing all the above ingredients, we believe that only a small fraction of the observed GRBs would be produced in this way.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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