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Orbit-induced Spin Precession as a Possible Origin for Periodicity in Periodically Repeating Fast Radio Bursts

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Abstract

FRB 180916.J0158+65 has been found to repeatedly emit fast radio bursts with a period of roughly 16 days. We propose that such periodicity comes from the orbit-induced spin precession of the emitter, which we assume to be a neutron star. Depending on the mass of the companion, the binary period ranges from several hundreds to thousands of seconds. Such tight binaries have relatively short lifetimes, and they are not likely to be products of gravitational decay from wide binaries. We comment on the relation of such binaries to GW190425 and the possibility of detecting them with LISA and LIGO.

Unified Astronomy Thesaurus concepts: Radio transient sources (2008); Radio bursts (1339); Compact binary stars (283)

1. Introduction

Fast radio bursts (FRB) are energetic pulses of gigahertz radio emission with durations from microseconds to milliseconds (Lorimer et al. 2007; Thornton et al. 2013; Masui et al. 2015; Katz 2016a; Ravi et al. 2016; CHIME/FRB Collaboration et al. 2019b). They have dispersion measures (DMs) between 300 and 1500 pc cm^{-3}, which is much larger than the line-of-sight DM contribution expected from the electron distribution of our Galaxy. Observations of the host galaxy of FRB 121102, which is also the first repeating FRB (Spitler et al. 2016), have confirmed the extra-Galactic origin of FRBs (Chatterjee et al. 2017; Tendulkar et al. 2017). Despite the unclear nature of FRBs, the confirmation of their cosmological origin makes FRBs useful cosmological probes; for example, they can be used to constrain the baryon number density (Deng & Zhang 2014; Keane et al. 2016; Jaroszynski 2019), measure cosmic proper distance (Yu & Wang 2017), find missing baryons (McQuinn 2014), constrain dark energy (Gao et al. 2014; Zhou et al. 2014), and test Einstein's Equivalent Principle (Wei et al. 2015).

To date, more than 1000 FRBs have been detected (Petroff et al. 2016), most of which were contributed by the Canadian Hydrogen Intensity Mapping Experiment Fast Radio Burst Project (CHIME/FRB; CHIME/FRB Collaboration et al. 2018, 2019a). FRB 180916.J0158+65 was first detected by CHIME together with the other eight new repeating FRBs (CHIME/FRB Collaboration et al. 2019b). With more than one year of operation, CHIME found a 16.35 ± 0.18 day periodicity (The CHIME/FRB Collaboration et al. 2020). This is the first FRB with periodicity identified.

Many models have been proposed to explain the extraordinary features of FRBs (for recent reviews, see Katz 2016a; Platts et al. 2019). Among all of the different models used to explain the repeating FRBs, the neutron star model is employed the most[4] to explore features such as the flares of the magnetars (Popov & Postnov 2010; Kulkarni et al. 2014; Lyubarsky 2014; Beloborodov 2017; Metzger et al. 2019), the similar origin of soft gamma-ray repeaters (Katz 2016b), the giant pulses from young pulsars (Lyutikov et al. 2016), the curvature radiation from the strong magnetic field of neutron stars (Kumar et al. 2017), the interaction of inspiraling double neutron stars (Wang et al. 2016; Zhang 2020), and even the possible connection of FRBs, gamma-ray bursts, and gravitational wave bursts (Zhang 2014, 2016). Based on the single neutron star model producing the fast radio emission, here we concentrate on the possible origin of the 16.35 ± 0.18 day periodicity. We suggest that the period could have arisen from the orbit-induced spin precession of a neutron star. This kind of precession has been suggested following Weisberg et al. (2010), who modeled the long-term polarized position angles of 81 pulsars, with precession periods in the range of 200–1300 days. We show the procession model in Section 2, and the conclusion and discussion are presented in Section 3.

2. Spin Precession of FRB 180916.J0158+65

Let us consider a compact binary system with mass M_1 and $M_2 = qM_1$ for the emitter and its companion respectively. The emitter, which is likely a neutron star, may rotate around its spin axis with periods ranging from milliseconds (millisecond pulsars) to seconds (magnetars). Therefore, the emission pattern in the emitter's sky may look like a disk or a ring depending on the opening angle of the emission with respect to the spin axis and the width of the emission cone. A schematic plot is given in Figure 1.

The spin $\boldsymbol{S}_1$ of the emitter may also precess due to spin–orbit coupling (Poisson & Will 2014):

$$\frac{d\boldsymbol{\mathcal{S}}_1}{dt} = \frac{G}{2a^3(1-e^2)^{3/2}c^2}\left[\left(4+\frac{3M_2}{M_1}\right)\boldsymbol{\mathcal{L}}\right]\times\boldsymbol{\mathcal{S}}_1, \qquad (1)$$

where e is the orbit eccentricity, G is the gravitational constant, c is the speed of light, $\boldsymbol{L}$ is the the orbital angular momentum vector, and a is the separation between two objects. We have neglected possible spin–spin coupling between the FRB emitter and its companion, which may become important if the

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[4] See, however, the shortcomings of the neutron star model and an explanation involving black hole jets (Katz 2019).

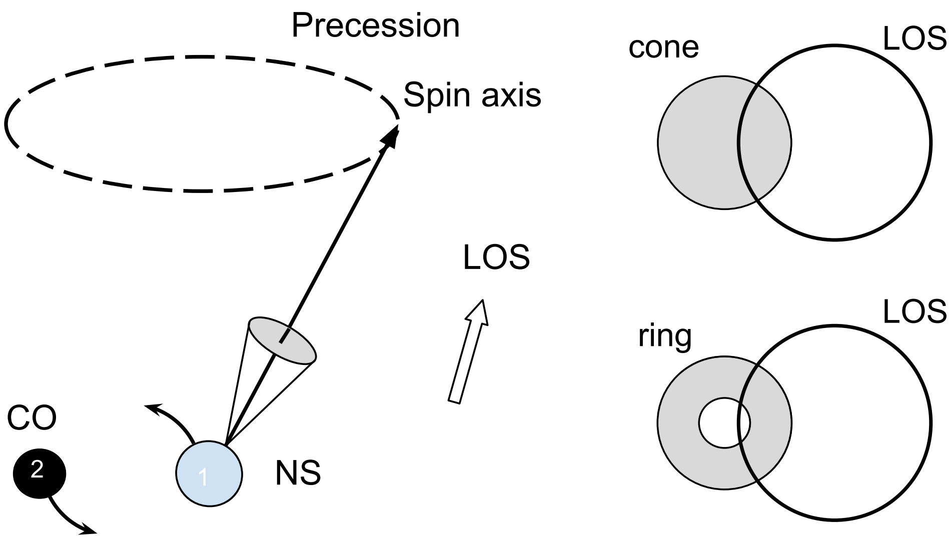

Figure 1. Left panel shows the schematic plot of the model. The neutron star (NS) emits sparse FRBs inside a solid angle along the spin axis. The emitting region is painted in gray and is much larger than the opening angle of each individual FRB. If the emission is similar to a pulsar, the region could be a ring rather than a polar cap. The companion, indicated as CO (compact object), could be a stellar-mass black hole, a neutron star, or a white dwarf. The precession is shown as a dashed circle. The line of sight (LOS) is plotted as an arrow. The right panel shows the configuration of the emitting region in relation to the line of sight in the frame of the neutron star, where the precession axis is located at the center of each circle. The overlap of the emitting region and the line of sight shows the observable fraction. The upper right subpanel corresponds to the case in which the FRB emitting region is located in the whole region along the spin axis. The lower right subpanel corresponds to the case in which the emitting cone rotates along the spin axis, which is similar to a pulsar emitting ring.

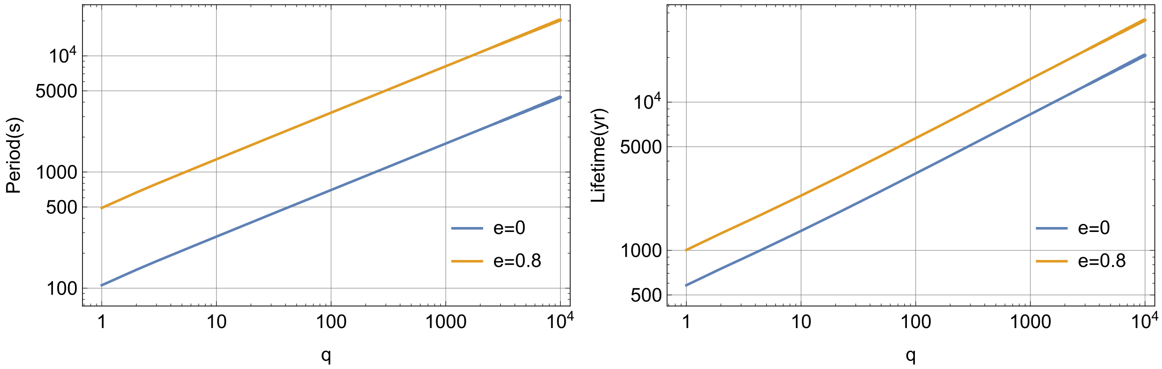

Figure 2. Left panel: the period of the compact binary as a function of the binary mass ratio. The emitter is assumed to be a 1.4 $M_\odot$ neutron star, and its spin precession period is 16 days. Right panel: the lifetime of such binaries under gravitational wave radiation.

companion is an intermediate mass black hole. With Equation (1), the spin precession frequency is just $\Omega_{\rm prec} = (4 + 3q)(GL/c^2)/(2a^3(\sqrt{1-e^2})^3)$, which we shall identify as 16 days for FRB 180916.J0158+65. The orbital frequency is given by

$$\Omega_{\rm orb} = \sqrt{\frac{G(M_1+M_2)}{a^3}} = \sqrt{\frac{GM_1(1+q)}{a^3}}, \tag{2}$$

and the magnitude of orbital angular momentum is

$$L = \frac{M_1M_2}{(M_1+M_2)}\Omega_{\rm orb}a^2\sqrt{1-e^2}. \tag{3}$$

Combining Equations (1)–(3), we can easily obtain the period of the binary as a function of the mass ratio, as depicted in Figure 2. It is also well approximated as

$$T \approx \frac{10^2}{(1-e^2)^{3/2}}q^{0.4}\ {\rm s}. \tag{4}$$

For stellar-mass binaries and binaries including an intermediate mass black hole, the orbital periods range from several hundreds of seconds to several thousands of seconds. As the FRB emitter is away from the galaxy center, it is unlikely that the companion is a supermassive black hole. The inferred distance is much smaller than the radius of a normal star, so the companion has to be a compact object. Such periods are smaller than those of any known neutron star binaries in our Galaxy.[5] In addition, the lifetime of such a system is (Peters 1964)

$$T_{\rm GW} = \frac{12}{19}\frac{c_0^4}{\beta} \times \int_0^e de \frac{x^{29/19}[1+(121/304)x^2]^{1181/2299}}{(1-x^2)^{3/2}}, \tag{5}$$

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[5] The shortest orbital period is on order of 100 minutes as shown at https://www.atnf.csiro.au/research/pulsar/psrcat/.

with

$$c_0 = a(1-e^2)e^{-12/19}\left[1+\frac{121}{304}e^2\right]^{-870/2299},$$
$$\beta = \frac{64}{5}\frac{G^3M_1M_2(M_1+M_2)}{c^5} \tag{6}$$

as shown in the right panel of Figure 2. These timescales are on the order of thousands of years for stellar-mass binaries, which is much shorter than the typical lifetimes of field binaries.[6] As $T_{\rm GW} \propto a^4$ and $T_{\rm prec} \propto a^{5/2}$, it is reasonable to expect that the distribution of similar systems in precession time should be

$$\frac{dN}{dT_{\rm prec}} \propto T_{\rm prec}^{3/5}, \tag{7}$$

unless there is a cutoff in the corresponding lifetime. This feature can be used to test this model as we find more repeating FRBs with periodicity. If there is an upper cutoff in precession time, we can use it to find the initial distance of the binary when it is formed. For FRB 180916.J0158+65, if the emitter is a magnetar with an active time $\sim 10^4$ yr, it is unlikely that this system originated from gravitational wave decay from a typical, wide-field binary. In addition, if we have indeed observed a short-period system, we should have observed many more FRBs (more than the 1000 FRB detections so far) given the large ratio between wide binaries and such tight binaries. FRB 180916.J0158+65 may instead come from formation channels with much closer distances.

Such a possibility may be related to the heavy binary neutron star mergers observed in GW190425 (The LIGO Scientific Collaboration et al. 2020), which are heavier than any known binary neutron stars in our Galaxy.[7] It was suggested that tight binaries exist in our Galaxy, because short-period binaries are difficult to observe with current methods. On the other hand, if this heavy neutron star pair is formed within a fast-merging channel, this may also account for the potential bias toward detection (Romero-Shaw et al. 2020; The LIGO Scientific Collaboration et al. 2020). Safarzadeh et al. (2020) argued that this leads to theoretical difficulties as traditional fast-merging channels (such as the case of BB unstable mass transfer) are unable to produce such frequent neutron star mergers. Nevertheless, these new observations will shed light on the formation processes of neutron stars.

These tight binaries fall into the detection band of Laser Interferometer Space Antenna (LISA; Danzmann 2000), or similar space-borne gravitational wave detectors such as Tianqin (Luo et al. 2016) or Taiji (Hu & Wu 2017). For a quasi-circular source, the event SNR can be computed as

$$\mathrm{SNR} \approx 2|h(f)|\sqrt{\frac{\Delta f}{S_{\rm LISA}(f)}}, \tag{8}$$

where $S_{\rm LISA}$ is the detector spectral density, $h(f)$ is the frequency domain waveform, $\Delta f = \dot{f}\, T_{\rm obs}$ is the frequency shift during the observation period, and $\dot{f}$ is induced by gravitational wave radiation. Setting the detection threshold for the signal-to-noise ratio to be 15, we plot the range of detection for LISA in Figure 3, with the observation time $T_{\rm obs}$ taken as 5 yr. We have assumed circular orbits here to avoid dealing with multi-frequency emission from elliptical orbits. FRB 180916.J0158+65 is estimated to be $\sim$100 Mpc away, which is clearly outside the detection range. However, if the FRB emission is beamed, it is reasonable to imagine that there are closer sources with FRB emission not pointing toward us. If the solid angle of emission is $\Delta\Omega$, then for any source observed with FRB emission at distance d, it is reasonable to expect another source as close as $d(\Delta\Omega/4\pi)^{1/3}$. If we take into account that maybe a fraction η of these sources are FRB emitters (i.e., the fraction of the active phase), then the estimator becomes

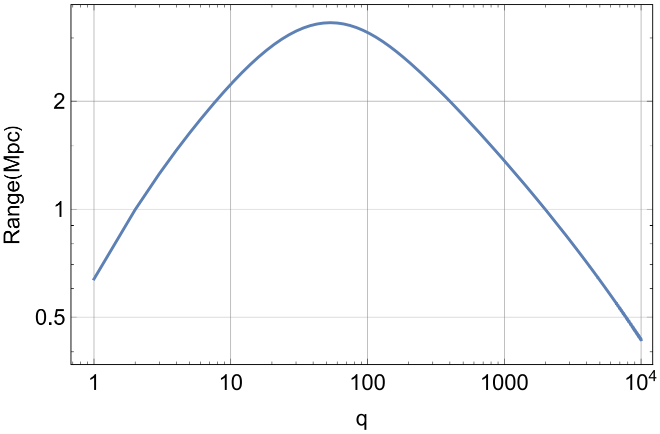

Figure 3. LISA detection range of systems considered in Figure 2, with the detection threshold SNR set to 15. The orbit is assumed to be circular for simplicity.

$$d_{\rm min} = d\left(\eta\frac{\Delta\Omega}{4\pi}\right)^{1/3} \sim 1.3\ \mathrm{Mpc}\left(\frac{d}{100\ \mathrm{Mpc}}\right) \times \left(\frac{\Delta\Omega}{10\ \mathrm{deg}^2}\right)^{1/3}\left(\frac{\eta}{10^{-2}}\right)^{1/3}. \tag{9}$$

In any case, it seems to be challenging to have a multi-messenger observation of such periodic repeaters with both FRB and gravitational wave measurements.

On the other hand, suppose that many periodic FRBs are indeed stellar-mass binaries in tight orbits. It is instructive to imagine as we find more of these systems, especially those at larger distances, that some of them may have lifetimes on the order of 10 years instead of thousands of years. As a result, we may first identify such periodic repeaters through FRB observation, and then measure the gravitational wave signals associated with binary mergers later on. Notice that the detection range of the Advanced Laser Interferometric Gravitational Wave Observatory (LIGO) is a few hundred megaparsecs and for Advanced LIGO Plus it is roughly $z \sim 0.2$ (Barsotti et al. 2018; Reitze et al. 2019).[8] Supposing the lifetime is 10 years, we can work out the expected precession timescales, which are several hours, as shown in Figure 4. Therefore, it may be useful to search for periodic repeaters with such periodicity in the future. This proposal itself can serve as a

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[6] In fact, the lifetimes of double neutron star systems are observed in the range from 86 Myr to well beyond Hubble time (Tauris et al. 2017).

[7] It is still possible that one (or both) of the compact objects in the binary system of GW190425 is a black hole (Yang et al. 2018; Han et al. 2020; Kyutoku et al. 2020; The LIGO Scientific Collaboration et al. 2020).

[8] Notice that if the companion is a white dwarf, the binary will merge before entering the LIGO band; though, the merging process may produce strong electromagnetic emissions.

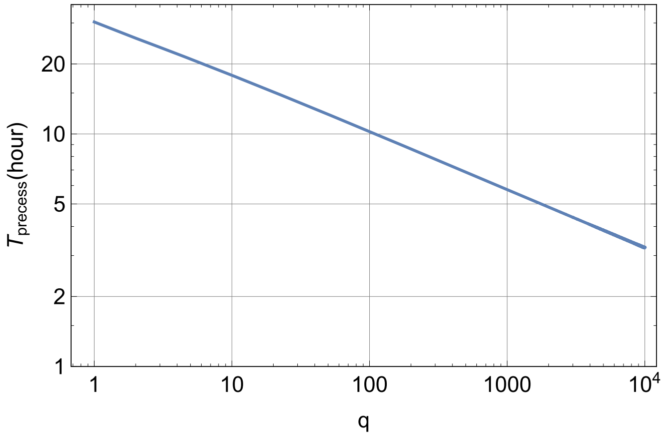

Figure 4. Expected precession timescale of the $1.4M_\odot$ neutron star within a stellar-mass binary, assuming that the binary lifetime is 10 years and the orbit is circular. This setting is useful for searching periodic FRBs that have the potential for multimessenger detection.

check for this precession model of periodic FRB repeaters. If we indeed observe such a short-precession time binary, we may even monitor the time-dependent evolution of the precession period, which should be $T_{\rm prec} \propto (t_c - t)^{5/8}$, with t_c being the coalescence time.

3. Conclusion and Discussion

In this work, we examine the possibility that FRB 180916.J0158+65 comes from a compact binary system, while the spin precession of the FRB emitter gives rise to the periodicity observed. This interpretation naturally predicts the period of the binary, which ranges from a few hundred seconds to a few thousand seconds, depending on the binary mass ratio. This type of tight binary has recently been discussed in relation to GW190425 in order to account for the possible observational bias of short-period systems. Because of its relatively short lifetime, we expect that this system also comes from a fast-merging channel, instead of being the product of gravitational wave decay from a wide binary. Besides the argument based on binary lifetime and rates, in light of the LIGO detection of heavy binary neutron stars in GW190425, it is also interesting to recognize that the more possible types of FRB emitters, magnetars, are indeed more massive than normal pulsars as they may come from more massive progenitors (Gaensler et al. 2005).

Although the periods of such systems fit directly into the LISA observation band (10^{-4}–10^{-1} Hz), it will be difficult to find them detachable in FRBs and gravitational waves. It is also unclear whether it is possible to extract the orbital period by electromagnetic observations, as FRBs repeat rather infrequently. However, it might be possible to find periodic repeaters with periods of several hours, which may lead to opportunities for gravitational wave detection by LIGO/Virgo or their upgrades later on. In addition, if the FRB emitter is a magnetar[9] and its companion is a black hole with a mass ratio $\gtrsim$5, the merger product will be a temporarily charged black hole. The discharge process takes several milliseconds due to strong gamma-ray emission, which may be observed by Fermi-LAT at a distance of $\sim$100 Mpc (assuming $B \sim 10^{15}$ G) or by a Cerenkov telescope such as in the work by CTA Consortium & Ong (2019; Pan & Yang 2019a).

We have included eccentricity in this simple model of orbit. For binaries produced by case BB unstable mass transfer, the eccentricity may already be small (Romero-Shaw et al. 2020), depending on the magnitude of supernova kicks. For binaries produced by dynamical interactions, the associated eccentricities have a small chance of being significant ($e > 0.1$; Rodriguez et al. 2018; Kremer et al. 2019; Pan & Yang 2019b).

During the preparation of this manuscript, Lyutikov et al. (2020) proposed a model in which a pulsar in a tight early B-star binary can arise during the 16 day periodicity due to orbital phase-dependent modulation. Lyutikov et al. (2020) disfavored the geodetic precession scenario by considering the energy budget from the orbit-induced electric potential. This is different from the model studied here, where we assume that the emission comes from a single emitter instead of the interaction between two stellar objects. Recently, Levin et al. (2020) and Zanazzi & Lai (2020) proposed the use of a deformed precessing magnetar to explain the observed periodicity. Note that in their models the precession rate should decay with time as the magnetar rotation slows down or the star deformation relaxes, whereas in this orbit-induced precession scenario the precession rate actually increases with time as the orbit shrinks by gravitational wave radiation.

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[9] Magnetars are thought to "last" for $\sim 10^4$ yr as the magnetic field gradually decays. This could be longer than the lifetime of such binaries.

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