Testing Models of Periodically Modulated FRB Activity

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5 October 2021

ABSTRACT

The activity of the repeating FRB 20180916B is periodically modulated with a period of 16.3 days, and FRB 121102 may be similarly modulated with a period of about 160 days. In some models of this modulation the period derivative is insensitive to the uncertain parameters; these models can be tested by measurement of or bounds on the derivative. In other models values of the uncertain parameters can be constrained. Periodic modulation of aperiodic bursting activity may result from emission by a narrow beam wandering within a cone or funnel along the axis of a precessing disc, such as the accretion discs in X-ray binaries. The production of FRB 200428 by a neutron star that is neither accreting nor in a binary then shows universality: coherent emission occurring in a wide range of circumstances.

Key words: radio continuum, transients: fast radio bursts, stars: binaries: general

1 INTRODUCTION

The activity of the repeating FRB 20180916B has been shown to be strongly modulated, with all detected bursts confined to about 30% of an ≈ 16.35 d cycle (CHIME/FRB Collaboration 2020; Pastor-Marazuela et al. 2020; Pilia et al. 2020; Pleunis et al. 2020). There is also evidence for an ≈ 160 d period in FRB 121102 (Rajwade et al. 2020; Cruces et al. 2021). This behavior was unexpected. Most FRB models are based on neutron stars with predicted rotational periods ranging from milliseconds (FRB as young energetic pulsars emitting giant pulses) to seconds (FRB related to Soft Gamma Repeaters (SGR); confirmed for FRB 200428 identified with SGR 1935+2154 with a period of 3.245 s). These models do not naturally lead to predictions that the aperiodic activity of repeating FRB would be periodically modulated with periods of many days.

A number of models for these long periods were soon proposed. These fell into three categories:

(i) Binary orbital periods, with a wind from one star either obscuring radio emission from its companion FRB source or interacting with that source (Ioka & Zhang 2020; Lyutikov et al. 2020; Popov 2020; Zhang & Gao 2020).

(ii) Precession of a strongly magnetized neutron star sweeping possible emission directions. In one version of this model, the neutron star precesses freely as a result of a magnetically distorted non-spherical figure (Levin, Beloborodov & Bransgrove 2020; Zanazzi & Lai 2020). In other versions it precesses under the influence of radiative torques (Sob’yanin 2020), the Newtonian torque of a fallback disc (Tong, Wang & Wang 2020), or relativistically (geodetic precession) in a very short period binary (Yang & Zou 2020).

(iii) Rotation of a neutron star source with the observed 16.3 day period (Beniamini, Wadiasingh & Metzger 2020).

Most of these models predict that the period will change, and some of their predictions can be cast in forms that are insensitive to the unknown parameters, permitting tests of the models. Sec. 2 quantifies these predictions. Sec. 3 develops the suggestion of Katz (2020) that long period modulation is the result of precession of the axis of an accretion disc under the torque of a binary companion star.

2 TESTING THE MODELS

It is straightforward to suggest a model that can produce the observed period, and the Introduction cites several. It is now two years since this modulation was first observed (CHIME/FRB Collaboration 2020). New data extend over 50 cycles (a duration of $T = 49P$): Pleunis et al. (2020) found a period $P = 16.33 \pm 0.12 \text{ d} = 1.411 \pm 0.010 \times 10^9 \text{ s}$ and Pastor-Marazuela et al. (2020) found a period $P = 16.29^{+0.15}_{-0.17} \text{ d} = 1.407^{+0.013}_{-0.015} \times 10^9 \text{ s}$, consistent with each other and with 16.35 d. $P$ and the angular modulation frequency $\Omega = 2\pi/P = 4.46 \pm 0.03 \times 10^{-6} \text{ s}^{-1}$ are accurately established.

Significant constraints can be placed on the rate of change

$$|\dot{\Omega}| = \frac{8|\Delta \phi|}{T^2} \lesssim 5 \times 10^{-16} \text{ s}^{-2}, \quad (1)$$

where it is assumed the period (or $\Omega$) is fitted to data from an entire data interval $T$; $|\Delta \phi| \lesssim 0.05 \text{ cycle} \approx 0.3 \text{ radian}$ is the phase deviation at the endpoints from exact periodicity at a period fitted to the midpoint of the data. As $T$ increases the constraint (1) will rapidly become stricter or a significant non-zero $\dot{\Omega}$ will be observed.

The following subsections address each proposed origin of
the 16.3 d period. Some may be excluded by Eq. 1; others will be tested in the future as $T$ increases.

### 2.1 Orbital Period

Orbital periods are expected to be extremely stable, and not usefully constrained by Eq. 1. However, LOFAR observed (Pleunis et al. 2020; Pastor-Marazuela et al. 2020) bursts from FRB 1908016B at frequencies as low as 110 MHz over the same or a larger fraction of the cycle as at the much higher frequencies observed by CHIME/FRB and Apertif. These authors pointed out that this argues against binary models in which a wind from the companion, more opaque at lower frequencies, limits the orbital phases at which a FRB can be observed. Ioka & Zhang (2020) and Lyutikov et al. (2020) propose different physical origins of this opacity. The resulting predicted phenomenologies are similar.

The phase delay (LOFAR detections occurring later in the 16.3 d cycle) might be explained by a reflecting or refracting wind whose flow is bent by the emitting neutron star’s gravity. If this carves out a transparent low density channel, as depicted by Ioka & Zhang (2020); Lyutikov et al. (2020), it might direct the low frequency radiation as did the Holmdel Horn Antenna (Crawford, Hogg & Hunt 1961) with which Penzias and Wilson discovered the 3 K background radiation. A plasma frequency of 50 MHz, sufficient to reflect (at grazing incidence) radiation in the LOFAR band, corresponds to an electron density $n_e \sim 4 \times 10^{12} \text{ cm}^{-3}$. For a plausible dimension $\sim 10^{12} \text{ cm}$ of a 16.3 d orbit this would imply a variation of dispersion measure, periodic with the orbital period, $\Delta \text{DM} \sim 10 \text{ pc cm}^{-3}$ of the higher frequency radiation that would penetrate such a plasma; this is not observed. If the plasma were dense enough to reflect the higher frequencies, there would be no phase delay between these bands.

### 2.2 Neutron Star Precession Period

A number of models have been proposed in which the observed modulation period is the precession period of a much faster rotating neutron star. No such fast rotation period has been observed in any FRB; even FRB 200428, known to be produced by a neutron star with a rotation period of 3.245 s, has not shown that period in its FRB activity.

In each of these models detection of the rotation period would constrain the other parameters; the cited original papers discuss these relationships. In this subsection I eliminate unknown parameters in favor of the observable time derivative of the precession rate that may soon either be measured or significantly constrained.

#### 2.2.1 Free Precession

Free precession of an aspherical neutron star deformed by magnetic stress was suggested by Levin, Beloborodov & Bransgrove (2020); Zanazzi & Lai (2020). In the model of Levin, Beloborodov & Bransgrove (2020) the model of Zanazzi & Lai (2020) leads to similar conclusions the precession angular frequency $\Omega_{\text{pre}}$ varies

$$\dot{\Omega}_{\text{pre}} = \frac{\Omega_{\text{pre}}}{2t_{sd}},$$

where $t_{sd}$ is the spindown age of the neutron star in FRB 20180916B extrapolated back to infinite $\Omega_{\text{pre}}$. Its actual age must be less than $t_{sd}$. The formulation of Eq. 2 removes any explicit dependence on the magnetic parameters or rotation rate; these are implicit in $t_{sd}$ and $\Omega_{\text{pre}}$. The phase deviation from a constant $\Omega_{\text{pre}}$ and period $P_{\text{pre}} = 2\pi/\Omega_{\text{pre}}$

$$\Delta \phi = \frac{1}{8} \dot{\Omega}_{\text{pre}} T^2 = -\frac{\pi}{8} \frac{T^2}{P_{\text{pre}} t_{sd}}.$$

The data span 49 cycles ($T \approx 7 \times 10^3$ s) and $|\Delta \phi| \lesssim 0.3 \text{ radian}$ may be estimated from Pleunis et al. (2020); Pastor-Marazuela et al. (2020), leading to a lower bound:

$$t_{sd} = \frac{\pi}{8} \frac{T^2}{P_{\text{pre}} \Delta \phi} \gtrsim 5 \times 10^9 \text{ s} \sim 150 \text{ y}.$$  

Because of its steep dependence on $T$, this lower bound on $t_{sd}$ may increase rapidly as observations continue. If, instead, a non-zero value of $\Delta \phi$ were measured then Eq. 4 would provide a specific value for $t_{sd}$. However, no value of nor lower bound on $t_{sd}$ could exclude this model because $t_{sd}$ is only an upper bound on the age of the object. The source’s actual age is less, perhaps much less, than $t_{sd}$ if the neutron star was born with spin and precession rates close to their present values. The only possible upper bound on $t_{sd}$ would be $T$, found if $\dot{\Omega}$ decreased by a factor $O(1)$ over that time; this would not provide any additional information because, by assumption, the source would have been observed over the time $T$.

The classic expression for the age of a rotating dipole, initially rotating very fast, is

$$t_{sd} = \frac{3}{4} \frac{I c^3}{\sin^2 \theta \mu^2} \frac{\Omega_{\text{rot}}^{-2}}{\Omega_{\text{pre}}},$$

where $I$ is its moment of inertia, $\theta$ the angle between rotation and dipole axes, $\mu$ the magnetic moment and $R$ the radius. In the model of Levin, Beloborodov & Bransgrove (2020) this may be used to rewrite Eq. 4 in terms of the polar dipole field $B = 2\mu/R^3$:

$$B = \sqrt{\frac{6}{\pi^2} \frac{I c^3 e^2 P_{\text{pre}}^3 \Delta \phi}{\sin^2 \theta \mu^2 R^6 T^2}},$$

where the dynamical asymmetry $e = k(B_{\text{int}}/10^{18} \text{ G})^2$ (Levin, Beloborodov & Bransgrove 2020) and $k$ is a dimensionless parameter presumably $O(1)$. $B_{\text{int}}$ is a measure of the internal magnetic field that produces the dynamical asymmetry, possibly $\gg B$ but not $\ll B$.

If $B_{\text{int}} \sim B$ then Eq. 6 may be rewritten, using the definition of $e$,

$$B \sim \frac{10^{36}}{k} \frac{G^2}{R} \sqrt{\frac{\sin^2 \theta R^6 \pi^3 T^2}{6I c^3 P_{\text{pre}}^3 \Delta \phi}} = 5 \times 10^{14} \frac{\sin \theta}{k} \sqrt{\frac{0.3 T}{\Delta \phi}} \frac{G}{\text{ yr}},$$

where $I = 10^{45} \text{ g cm}^2$ and $R = 10^6 \text{ cm}$ have been assumed. Because only an upper limit to $\Delta \phi$ is known, this last expression is only a lower bound on $B$ that will increase with $T$ as data accumulate. It is an indication of the values (if a nonzero

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1. Levin, Beloborodov & Bransgrove (2020) identify $t_{sd}$ with its actual age, but the neutron star could have been born with spin and precession rates close to their present values.
$\Delta \phi \propto T^2$ is measured) or bounds that may be placed by future observations. It is now consistent with expectations for strongly magnetized neutron stars, such as the sources of Soft Gamma Repeaters (SGR), but may exceed such expectations in the future.

### 2.2.2 Radiatively Driven Precession

In the radiatively driven precession model of Sob’yanin (2020) the rotation period $P_{\text{rot}}$ and precession period $P_{\text{pre}}$ are proportional:

$$P_{\text{rot}} = \left( \frac{B}{7.45 \times 10^{17} \text{ G}} \right)^2 P_{\text{pre}},$$ (8)

where $B$ is the polar (not equatorial, the more usual parameter) field of a dipole. Combining this with the spindown equation

$$\frac{dP_{\text{rot}}}{dt} = \frac{2}{3} (2\pi)^3 \mu^2 \sin^2 \theta \frac{2}{T c^2 P_{\text{rot}}},$$ (9)

where the magnetic dipole moment $\mu = BR^3/2$, yields

$$\dot{\Omega}_{\text{pre}} = \frac{2}{3} (2\pi)^3 \frac{R^3}{c^4} \frac{2}{P_{\text{pre}}} \sin^2 \theta \left( \frac{7.45 \times 10^{17} \text{ G}}{2} \right)^4,$$ (10)

where $R$ is the neutron star’s radius, $I$ its moment of inertia and $\theta$ the angle between the angular momentum and magnetic dipole axes. This form replaces the explicit dependence on the unknown $P_{rot}$ with a dependence on $B$ and the observed $P_{pre}$. This can be used to relate $B$ to a phase shift $\Delta \phi$ observed over a time $T$, using Eq. 1:

$$B = \frac{(2\pi)^3}{4\sqrt{3}} \frac{R^3}{c^4 P_{\text{pre}}} \frac{T}{\sin^2 \theta} \frac{1}{\sqrt{\Delta \phi}}.$$ (11)

For the conventional values $R = 10^6 \text{ cm}$ and $I = 10^{45} \text{ g-cm}^2$, the polar dipole field

$$B = 6.4 \times 10^{13} \text{ cm}^{-1} \frac{\sin^2 \theta}{\sqrt{\Delta \phi}} \geq 2.5 \times 10^{14} \text{ cm}^{-1} \frac{\sin^2 \theta}{\sqrt{\Delta \phi}},$$ (12)

where the present $T = 2.2 \text{ y}$ and $|\Delta \phi| \lesssim 0.3 \text{ radian}$ have been taken. Even for the maximum possible $\sin^2 \theta = 1$ this bound is consistent with the magnetic fields estimated for SGR, and is numerically similar to the corresponding Eq. 7 for the free precession model of Levin, Beloborodov & Bransgrove (2020); Zanazzi & Lai (2020). It cannot become large enough to exclude the radiative precession model of Sob’yanin (2020) on the basis of requiring an implausibly large field, even assuming $\sin^2 \theta = 1$, for many years (depending on how large a field is considered implausible).

Just as in Sec. 2.2.1, a value of $t_{sd}$ inferred from $B$ cannot by itself exclude or constrain this model.

### 2.2.3 Geodetic Precession

Yang & Zou (2020) suggest periodic modulation of observed activity is produced as the spin axis of a rotating neutron star precesses in the gravity of a binary companion in a misaligned orbit. This relativistic effect (geodetic precession) does not depend on any asphericity of the neutron star. Bursts emitted in a cone around the spin axis may be directed towards the observer only during some fraction of the precession cycle. As the orbit decays by emission of gravitational radiation the precession rate $\Omega_{\text{pre}}$ increases, producing a phase advance $\Delta \phi$. The observational constraint (Pluenis et al. 2020; Pastor-Marazuela et al. 2020) on any such advance constrains the orbital parameters.

Using the standard results for the shrinkage of the orbit, taken to be circular with radius $a$,

$$\frac{da}{dt} = -\frac{64 (GM_1)^3 q(1+q)}{5} \frac{\sin^2 \theta}{a^3},$$ (13)

where $M_1$ is the mass of the source of the FRB and the mass ratio $q = M_2/M_1$, and for the precession rate

$$\Omega_{\text{pre}} = \frac{(4+3q)q (GM_1)^{3/2}}{1+q \sqrt{1+q} 2a^5/2c^2},$$ (14)

we find

$$\Omega_{\text{pre}} = 32 \frac{(GM_1)^3}{a^2 c^2} q(1+q)\Omega_{\text{orb}}.$$ (15)

Using Eq. 14 to find $a$ in terms of the observed period $P_{\text{pre}}$ and $\Omega_{\text{pre}} = 2\pi/P_{\text{pre}}$

$$\dot{\Omega}_{\text{pre}} = 32 \frac{2^{8/5}(1+q)^{3/5}}{q^{2/5}(4+3q)^{8/5}} \frac{(GM_1)^{3/5}}{c^{9/5}} \Omega_{\text{orb}}^{13/5}.$$ (16)

The explicit dependence on the unknown $a$ and $\Omega_{\text{orb}}$ has been eliminated. The dependence on $M_1$ and $q$ is not steep: the second factor is 0.47 for $q = 1$ and approaches $(2/3)^{8/5} q^{-2/5}$ as $q \to \infty$, as shown in more detail by Yang & Zou (2020), and in this model $\Omega_{\text{pre}}$ is the observed modulation frequency.

This model makes a testable quantitative prediction. Taking $M_1 = 1.4M_\odot$ and $q = 1$

$$\dot{\Omega}_{\text{pre}} = 1.5 \times 10^{-16} \text{ s}^{-2},$$ (17)

and

$$\Delta \phi = \frac{1}{8} \Omega_{\text{orb}} T^2 = 0.018 \left(\frac{T}{1 \text{ y}}\right)^2 \text{ radian}.$$ (18)

With the present $T \approx 2.2 \text{ yr}$ the predicted phase drift is approaching the accuracy of measurement. The prediction will soon be tested (provided the FRB remains active). Note that $\Delta \phi$ is four times larger if the period is accurately determined at one end of the data duration $T$ rather than fitted to the entire duration with uniform weight; this may be applicable if detected bursts are non-uniformly distributed in time.

### 2.2.4 Newtonian Precession by a Fall-back Disc

Tong, Wang & Wang (2020) suggest the direction of FRB radiation is modulated by the precession of a neutron star under the Newtonian gravitational influence of a fall-back disc. This model makes the qualitative prediction that the modulation period should increase as the disc dissipates, some matter accreting onto the neutron star, possibly making SGR and Anomalous X-Ray Pulsar (AXP) emission (Katz, Toole & Unruh 1994), and some driven to greater distances. If detected bursts are non-uniformly distributed in time.

$$t_{\text{sd}} = \frac{\Omega_{\text{pre}}}{t_{\text{diss}}} \sim \frac{\Omega_{\text{pre}}}{t_{\text{diss}}}.$$ (19)

The dissipation time is unknown; guessing $t_{\text{diss}} \sim 10^{11} \text{ s}$ from the ages of SGR (inferred from the ages of the supernova remnants containing them), suggests $\Omega_{\text{pre}} \sim 4 \times 10^{-17} \text{ s}^{-2}$. A phase advance $\Delta \phi = 1 \text{ radian}$, unambiguously detectable, would occur in a time $T \sim \sqrt{8/\Omega_{\text{pre}}} \sim 15 \text{ y}$. 

MNRA 000, 1–5 (2020)
Any quantitative prediction, as well as the model itself (almost nothing is known about fall-back discs beyond the evidence that many white dwarfs and at least a few neutron stars are surrounded by some orbiting material) depends on several speculative assumptions. Even the sign of $\Omega_{\text{pre}}$ is uncertain, because matter may move inward, increasing $\Omega_{\text{pre}}$, as well as moving outward or being lost, decreasing $\Omega_{\text{pre}}$.

2.3 Neutron Star Rotation

Beniamini, Wadiasingh & Metzger (2020) suggested that the 16 day period may be the rotation period of a neutron star. The longest known neutron star rotation periods in X-ray binaries are about 1000 s, about a thousand times shorter that of FRB 20180916B. 1E 161348−5055 has been suggested (De Luca et al. 2006) to be a single neutron star rotating with a 6.67 hour period, about 50 times shorter than that of FRB 20180916B.

A neutron star, estimated to have $I \approx 10^{45}$ g-cm$^2$, accreting freely infalling matter at its surface, would spin up from rest to a 16 day period by the accretion of $10^{-10}$ of its mass, provided the angular momentum of the accreted mass were all aligned. Accretion from a disc would require only $1/\sqrt{2}$ as much mass. Interaction of either accretion flow with a magnetosphere at radius $10^9$ cm would reduce these mass fractions by a factor of about 30. Neutron stars interacting with the winds of binary companions appear to be spun down by a “propellor effect” (usually they are not accreting; they usually spin up when accreting) to periods as long as hundreds of seconds.

These considerations can be restated in terms of bounds on any systematic torque $N$, of accretional or other origin, placed by the observed bound Eq. 1 on the rate of change of the modulation frequency:

$$N \lesssim \frac{8A\phi}{T^2} I \sim 5 \times 10^{29} \text{dyne-cm.}$$  \hspace{1cm} (19)

If interpreted as the result of accretion onto the surface of a neutron star, the corresponding upper bound on the accretion rate $\sim 3 \times 10^{13}$ g/s $\approx 5 \times 10^{-13} M_\odot$/y. This is much less than accretion rates in known massive X-ray (NS-OB star) binaries.

Although not demonstrably impossible, a single neutron star with a spin period of 16 days may be implausible. The existence of single fast young pulsars like the Crab suggests rapid (periods of tens of ms) initial spin. If collapsed from a stellar core of white dwarf density, conserving angular momentum, a neutron star with a 16 day rotation period would imply a pre-collapse core’s rotation period of thousands of years. Even the 6.67 h period of 1E 161348−5055 might have other explanations, such as the orbital period if it has a low mass companion.

The AM Her stars (“polars”) may be informative. The rotation of these binary magnetic white dwarves is synchronous with their orbits. Synchronism is produced by magnetostatic interaction (Joss, Katz & Rappaport 1979), as demonstrated by the preferential orientation (Cropper 1988) of the white dwarf’s magnetic dipole in the rotating frame (Katz 1989). A similar phenomenon might make FRB 20180916B rotate synchronously with a companion star in a 16.3 d orbit, but the maximum synchronizing torque would be small:

$$N_{\text{max}} \sim \frac{\mu^2}{a^3},$$  \hspace{1cm} (20)

where $\mu \approx 10^{33} B_{15}^3 \text{G-cm}^3$ is the neutron star’s magnetic moment. For a 16 day period $a \sim 10^{12}$ cm and $N_{\text{max}} \sim 10^{30} B_{15}^3 \mu$, dyne-cm.

Synchronism would be disrupted by an accretion rate $\gtrsim 10^{-13} M_\odot$/y, but might be maintained if the accretion rate were very small. Eq. 20 also sets an upper limit to the synchronizing torque, achieved only if the effective coupling is strongly dissipative ($Q \sim 1$ if considered as an oscillator). Synchronization might be possible in a time $t$ if the initial neutron star rotation rate $\Omega_0 < N_{\text{max}} t/(tQ) \sim [t/(3 \times 10^4 Qy)] B_{15}^3 s^{-1}$. The implied magnetic field at the companion would be $\sim$mG, roughly comparable to that inferred over a larger distance scale (Katz 2021) for the environment of FRB 121102. The maximal accretion rate consistent with synchronism also corresponds to an electron density comparable to that estimated for the magnetoionic environment of FRB 121102. However, FRB 20180916B does not show the large and rapidly varying rotation measure of FRB 121102, so it is unclear if the parameters inferred for one of these objects can apply to the other.

3 ACCRETION DISC PRECESSION

Many X-ray binaries (Sood et al. 2007; Townsend & Charles 2020) and cataclysmic variables (Armstrong et al. 2013) show superorbital periods explained as precession of the axes of accretion discs misaligned with the orbital plane (Katz 1973, 1980). These periods are tens to a few hundred days, consistent with the period of FRB 20180916B. This model was confirmed by observation of sideband periods in SS 433 (Katz et al. 1982) and of the phases of the disc eclipses in Her X-1 (Levine & Jernigan 1982). Alternative models have been discussed by Zdziarski, Pooley & Skinner (2011) and are not favored.

Misalignment of the disc and orbital planes can be considered a perturbation to the lowest energy state of a disc, in which it lies in the orbital plane. Precession is observed in many, if not all, of those binaries that are observed at large inclination so that the disc may eclipse the compact object or the central, high-energy emitting, regions of the disc itself (in SS 433 measurement of the Doppler shifts of the jets makes eclipse unnecessary).

The mechanism of excitation is unclear. Speculations have included radiative feedback from the outer disc shadowing the mass-losing companion. A companion with misaligned spin would directly feed a misaligned disc, but spin alignment is expected to occur at least as fast as orbital circularization, and where accurately measured (as in Her X-1) the orbits are accurately circular. If the mass-losing star does have a misaligned spin, then the rate of precession of the disc would be the sum of its precession rate under the companion’s torque and the precession rate of the companion under the torque of the compact object. The second term will generally be smaller because the mass of most stars, especially in their mass-losing phase of advanced evolution, is centrally concentrated.

In this model of the 16.3 d period of FRB 20180926B based on precession of an accretion disc in a mass-transfer binary
the bursts must be confined within a cone or funnel around the disc axis (Katz 2017) whose width $\delta \theta$ is less than the amplitude of precession $\Delta \theta$. Then $2\delta \theta/(2\pi \Delta \theta) \approx F$, where $F \approx 0.3$ is the fraction of the 16.3 d cycle over which bursts are observed. This does not provide any clue to the values of $\delta \theta$ and $\Delta \theta$, other than their ratio.

The existence of FRB 200428, a repeating FRB for which there is no evidence of periodic modulation, produced by a single non-accreting neutron star, is not evidence against models of modulated FRB that involve binary companions or accretion discs if coherent emission occurs in a wide range of environments. The existence of short and long gamma-ray bursts, with similar phenomenology but produced by different astronomical events, is another example of phenomenological universality.

4 DISCUSSION

Models may be distinguished by the behavior of the modulation period. Orbital periods and orbitally-locked rotation periods involve the motion of massive bodies and are expected to be extremely stable. An exception to this is geodetic spin precession in very compact binaries, whose period shortens at a quantitatively predictable rate (Eq. 16). This rate is only weakly dependent on unknown parameters, and the model is therefore testable. Free and radiative precession of an isolated neutron star is expected to slow smoothly on the star’s spin-down time scale, although their rates of decline depend on poorly known parameters (Eqs. 2, 10).

Models involving fall back or accretion discs make no specific predictions and are sensitive to unknown parameters (Eq. 10). These models, unlike others, are consistent with irregular variation of the period. In any model involving disc dynamics the period depends on the mass distribution in the disc, whose behavior is not known, and may fluctuate. Observations of the best-studied accretion discs, those around Her X-1 and in SS 433, indicate their periods vary slightly, with $\Delta P/P \sim 0.01$, without a systematic trend. This is in contrast to precession of a neutron star driven by a fall-back disc, whose period would be expected to increase as the disc dissipates, but on the (unknown) time scale of the age of the neutron star and disc.

The measured nonzero changes in RM and upper bounds on changes in DM (Pleunis et al. 2020) of FRB 20180916B imply that the magnetic field in the region in which the RM change is produced $B \gtrsim 3 \mu G$. This is consistent with interstellar fields, and, unlike FRB 121102 (Katz 2021), does not require an extraordinary local magnetoionic environment.

DATA AVAILABILITY

This theoretical study did not obtain any new data.

REFERENCES

Armstrong, E., Patterson, S., Michelsen, E. et al. 2013 MNRAS 435, 707.

Beniamini, P., Wadiasingh, Z. & Metzger, B. D. 2020 MNRAS 496, 3390 (arXiv:2003.12509).

CHIME/FRB Collaboration 2020 Nature 582, 351 (arXiv:2001.10275).

Crawford, A. B., Hogg, D. C. & Hunt, L. E. 1961 Bell System Tech. J. 40, 1095.

Cropper, M. 1988 MNRAS 231, 597.

Crucis, M., Spitler, L. G., Scholz, P. et al. 2021 MNRAS 500, 448 (arXiv:2008.03461).

De Luca, A., Caraveo, P. A., Mereghetti, S., Tiengo, A. & Bignami, G. F. 2006 Science 313, 814.

Ioka, K. & Zhang, B. 2020 ApJ 893, L26 (arXiv:2002.08297).

Joss, P. C., Katz, J. I. & Rappaport, S. A. 1979 ApJ 230, 176.

Katz, J. I. 1973 Nature Phys. Sci. 246, 87.

Katz, J. I. 1980 ApJ 236, L127.

Katz, J. I. 1989 MNRAS 239, 751.

Katz, J. I. 2017 MNRAS 467, L96. (arXiv:1611.01243)

Katz, J. I. 2020 MNRAS 494, L64 (arXiv:1912.00526).

Katz, J. I. 2021 MNRAS 501, L76 (arXiv:2011.11666).

Katz, J. I., Anderson, S. F., Margon, B. & Grandi, S. A. 1982 ApJ 260, 780.

Katz, J. I., Toole, H. A. & Unruh, S. H. 1994 ApJ 437, 727.

Levin, Y., Beloborodov, A. M. & Bransgrove, A. 2020 ApJ 895, L30 (arXiv:2002.04595).

Levine, A. M. & Jernigan, J. G. 1982 ApJ 262, 294.

Lytutkov, M., Barkov, M. V. & Giannios, D. 2020 ApJ 893, L39 (arXiv:2002.01920).

Pastor-Marazuela, I., Connor, L., van Leeuwen, J. et al. 2020 arXiv:2012.08348.

Pilia, M., Burgay, M., Possenti, A. et al. 2020 ApJ 896, L40 (arXiv:2003.12748).

Pleunis, Z., Michilli, D., Bassa, C. G. et al. 2020 arXiv:2012.08372.

Popov, S. B. 2020 Res. Notes Am. Astron. Soc. 4, 98 (arXiv:2006.13037).

Rajwade, K. M., Mickaliger, M. B., Stappers, B. W. et al. 2020 MNRAS 495, 3551 (arXiv:2003.03596).

Sol’yanin, D. N. 2020 MNRAS 497, 1001 (arXiv:2007.01616).

Sood, R., Farrell, S., O’Neill, P. & Dieters, S. 2007 Adv. Sp. Res. 40, 1528.

Tong, H., Wang, W. & Wang, H.-G. 2020 Res. Astron. Ap. 20, 142 (arXiv:2002.10265).

Townsend, L. J. & Charles, P. A. 2020 MNRAS 495, L139 (arXiv:2004.14207).

Yang, H. & Zou, Y. -C. 2020 ApJ 893, L31 (arXiv:2002.02553).

Zanazzi, J. J. & Lai, D. 2020 ApJ 892, L15 (arXiv:2002.05752).

Zdziarski, A. A., Pooley, G. G. & Skinner, G. K. 2011 MNRAS 412, 1985.

Zhang, X. & Gao, H. 2020 MNRAS 498, L1 (arXiv:2006.10328).