Precession and Jitter in FRB 180916B

J. I. Katz,1⋆
1Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, Mo. 63130 USA

20 July 2022

ABSTRACT
Recent CHIME/FRB observations of the periodic repeating FRB 180916B have produced a homogeneous sample of 44 bursts. These permit a redetermination of the modulation period and phase window, in agreement with earlier results. If the periodicity results from the precession of an accretion disc, in analogy with those of Her X-1, SS 433, and many other superorbital periods, the width of the observable phase window indicates that the disc axis jitters by an angle of about 0.14 of the inclination angle, similar to the ratio of 0.14 in the well-observed jittering jet source SS 433.

Key words: radio continuum, transients: fast radio bursts, accretion, accretion discs, stars: black holes, stars: magnetars

1 INTRODUCTION
The bursts of the repeating FRB 180916B have been shown to be confined to a window about five days wide that repeats with a period of 16.3 days (CHIME/FRB Collaboration 2020; Pleunis et al. 2021). A period of 160 days has also been suggested for FRB 121102 (Rajwade et al. 2020). A number of models of this behavior have been proposed, but none have yet been definitively tested (Katz 2021a; McKinven et al. 2022) provide references to the original literature.

The recent extended study of FRB 180916B by McKinven et al. (2022) reported 44 bursts observed by CHIME/FRB. This sample is expected to be homogeneous because CHIME/FRB is an unsteered transit instrument whose observations do not depend on a choice of observing times thought to be propitious for detection, or other times for other reasons. There are several likely contributions to variations in sensitivity: varying amplifier gain, a varying number of feeds down, varying weather, varying electromagnetic interference, changes in detection threshold and shutdowns for maintenance or upgrades (McKinven 2022). These are unlikely to be correlated with phase in the 16 day cycle and therefore do not affect the mean dependence of burst activity on phase, although they add stochastic noise by reducing the number of observed bursts. Were they correlated with 16 day phase, we would not accept the reality of the 16 day period.

This paper investigates the implications of these data for the hypothesis (Katz 2020; Sridhar et al. 2021) that the periodicity results from the emission of bursts along the rotation axis of a precessing accretion disc in a binary system. Precessing discs are observed in Her X-1/HZ Her, the prototype (type specimen or holotype in biological nomeclature) superorbital binary with an orbital period of 1.7 d and a superorbital period of 35 d (Katz 1973) in which X-rays are emitted by a neutron star, in SS 433 with an orbital period of 5.6 d and a superorbital period of 164 d (Katz 1980) in which an accretion disc around a black hole launches a sub-relativistic jet along its axis, and in many other mass-transfer binaries.

The periodicity and period of FRB 180916B are well established (CHIME/FRB Collaboration 2020; Pleunis et al. 2021; McKinven et al. 2022). The chief purposes of this study were to examine the distribution of burst phases about exact periodicity, to compare to observations of SS 433, and to investigate the applicability of the jittering precessing beam model to FRB 180916B.

2 THE PERIOD
The times of the 44 bursts observed by McKinven et al. (2022) may be used to redetermine the modulation period. One way of doing this is to calculate the periodogram of the burst times. This is defined by

\[ A(P) = \sqrt{C^2(P) + S^2(P)}, \] (1)

by a neutron star, in SS 433 with an orbital period of 5.6 d and a superorbital period of 164 d (Katz 1980) in which an accretion disc around a black hole launches a sub-relativistic jet along its axis, and in many other mass-transfer binaries. Attributing periodicity to disc precession follows from the hypothesis (Katz 2017) that repeating FRB are produced in accretion disc funnels.

Fast radio bursts (FRB) have not been detected from known superorbital binaries, but the line of sight is aligned with the disc axis in only a small fraction of such objects, and only intermittently because the disc axis is, in at least some of them, precessing and jittering, so this might be an observational selection effect. Alternatively, those emitting FRB may be distinguished from those that do not in some other, as yet not understood, manner (Katz 2021b): obvious candidates include the mass and nature (neutron star or black hole) of the central object, accretion rate, turbulence in the accretion flow, and the magnetic field in the accreting matter.

The periodicity and period of FRB 180916B are well established (CHIME/FRB Collaboration 2020; Pleunis et al. 2021; McKinven et al. 2022). The chief purposes of this study were to examine the distribution of burst phases about exact periodicity, to compare to observations of SS 433, and to investigate the applicability of the jittering precessing beam model to FRB 180916B.

* E-mail katz@wuphys.wustl.edu

© 2022 The Authors
where
\[ C(P) = \sum_n \cos \frac{2\pi T_n}{P} \]
\[ S(P) = \sum_n \sin \frac{2\pi T_n}{P}, \]
where \( T_n \) is the time of the \( n \)-th burst and \( P \) is the period.

The periodogram of these 44 bursts for \( 15.95 \text{ d} \leq P \leq 16.71 \text{ d} \) is shown in Fig. 1. The best estimate of the period is the value for which the periodogram is maximum, \( P = 16.315 \text{ d} \). This is close to and consistent with values obtained from previous data by CHIME/FRB Collaboration (2020); Pleunis et al. (2021).

### 3 BURST PHASES

Alternatively, the mean and the standard deviation of the phases of the individual bursts may be computed as functions of the period. The results are shown in Fig. 2. Unsurprisingly, the standard deviation is a minimum for the same \( P = 16.315 \text{ d} \) as the maximum of the periodogram.

The phases of the 44 bursts, with phase 0.5 defined as the mean phase with the best-fit period, are shown in Fig. 3. Their standard deviation is 0.071 cycles, or 1.16 d. The period, assuming a Gaussian random distribution of phase offsets, is \((\pm 1\sigma \text{ error estimate})\)

\[ P = 16.315 \pm 0.175 \text{ d}, \]
consistent with earlier determinations (CHIME/FRB Collaboration 2020; Pleunis et al. 2021). The observed distribution is consistent with the Gaussian fit.

### 4 JITTER

One possible model of the periodicity of FRB 180916B attributes it to emission along the angular momentum axis of an accretion disk that precesses as a result of the torque exerted by a mass in orbit around the accreting object. The most quantitatively-studied such system is the binary SS 433.

The mass of its components long been uncertain, but the most recent determination (Bowler 2018) indicates the accreting object is a black hole of mass \( 15 \pm 2 M_\odot \), and its stellar companion has a mass of about \( 20 M_\odot \).

The axis of the precessing disc of SS 433 jitters around its mean precession (Katz & Piran 1982; Iijima 1993; Collins & Garasi 1994; Kubota et al. 2010). It is uniquely well observed because its sub-relativistic jet of ionized gas, assumed to be emitted along its axis, radiates emission lines whose Doppler shifts are measured quantitatively (Milgrom 1981; Margon 1984; Fabrika 2004). Observations of other precessing discs (Levine & Jernigan 1982) also suggest jitter about their mean motion.

We assume the FRB, and the jet in SS 433, are emitted
along the instantaneous angular momentum axis of their discs and that any deviation be small compared to the amplitude of the jitter. The distribution of jitter angles in SS 433 is obtained directly from the jet’s Doppler shifts (Katz & Piran 1982; Iijima 1993; Collins & Garasi 1994; Kubota et al. 2010). Its half-width $\Delta \theta \approx 0.05$ radian. The precession angle $\theta \approx 20^\circ \approx 0.35$ radian and $\Delta \theta/\theta \approx 0.14$. In the proposed model of FRB 180916B the observed standard deviation of phase $\Delta \phi \approx 2\pi \times 0.071$ radian implies (because 0.071 is the half-width in phase) $\Delta \theta/\theta \approx (\Delta \phi/\pi) \approx 0.14$. The equality to the corresponding value for SS 433 is surely fortuitous, but the fact that they are comparable is consistent with the proposed model.

5 DISCUSSION

The observation (Pastor-Marazuela et al. 2021) that the activity window is wider at low frequencies is consistent with emission in an accretion funnel. Lower frequency waves may be refracted away from the funnel axis by the plasma of the jet, and lower frequency emission may be produced further from the central compact object where the angular width of the funnel is wider (Sridhar et al. 2021).

The known object most closely resembling the model presented here is SS 433; we are always far from its beam axis (Milgrom 1981; Margon 1984; Fabrika 2004) so the absence of FRB from SS 433 does not disprove the model of FRB emission along a disc axis. Nor does the identification of FRB 200428 with a Soft Gamma Repeater that does not appear to have an accretion disc, if repeating and apparently non-repeating FRB are produced by different classes of sources (Katz 2022). At extra-Galactic distance FRB 200428, if close enough to be observed at all, would be an apparent non-repeater, unlike the repeating FRB 180916B. The hypothesis that repeating FRB are emitted along a disc axis is independent of the nature of the object emitting the FRB, and does not require that the disc precess; precession is only required when FRB activity is modulated periodically, as it is in FRB 180916B.

The rarity of objects like SS 433 (there appears to be only one in our Galaxy), combined with the fortuitous alignment required to observe emission collimated with the axis of a precessing jet, may explain the low density of observed repeating FRB in the Universe. This is difficult to quantify because of the uncertain abundance of such possible FRB sources and the uncertain accuracy of alignment and duration and sensitivity of observation required for their discovery.

The binary precessing disc model is the only model of the periodic modulation of FRB activity that has been observed in another object. The results presented here constrain its parameters if it is correct.

ACKNOWLEDGEMENTS

I thank R. Mckinven and T. Piran for useful discussions.

DATA AVAILABILITY

This theoretical study did not generate any new data.

REFERENCES

Bowler, M. G. 2018 A&A 619, L4.
CHIME/FRB Collaboration 2020 Nature 582, 351.
Collins, G. W. II & Garasi, C. J. 1994 ApJ 431, 836.
Fabrika, S. 2004 Astrophysics Space Physics Rev. 12, 1.
Iijima, T. 1993 ApJ 410, 295.
Katz, J. I. 1973 Nature Phys. Sci. 246, 87.
Katz, J. I. 1980 ApJ 236, L127.
Katz, J. I. 2017 MNRAS 471, L92.
Katz, J. I. 2020 MNRAS 494, L64.
Katz, J. I. 2021a MNRAS 502, 4664.
Katz, J. I. 2021b MNRAS 508, L12.
Katz, J. I. 2022 arXiv:2203.03675.
Katz, J. I. & Piran, T. 1982 Ap. Lett. 23, 11.
Kubota, K., Ueda, Y., Kawai, N. et al. 2010 PASJ 62, 323.
Levine, A. M. & Jernigan, J. G. 1982 ApJ 262, 294.
Margon, B. 1984 ARA&A 22, 507.
Mckinven, R. 2022 personal communication.
Mckinven, R., Gaensler, B. M., Michilli, D. et al. 2022 arXiv:2205.09221.
Milgrom, M. 1981 Vistas Astr. 25, 141
Pastor-Marazuela, I., Connor, I., van Leeuwen, J. et al. 2021 Nature 596, 505.
Pleunis, Z., Michilli, D., Bassa, C. G. et al. 2021 ApJ 911, L3.
Rajwade, K. M., Mickaliger, M. B., Stappers, B. W. et al. 2020 MNRAS 495, 3551.
Sridhar, N., Metzger, B. D., Beniamini, P. et al. 2021 ApJ 917, 13.