Symmetry Breaking in Repeating Fast Radio Bursts

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14 September 2022

ABSTRACT
Repeating Fast Radio Bursts show temporal symmetry breaking on millisecond time scales (the “sad trombone”). On a time scale of days the repetitions of FRB 180916B occur at frequency-dependent phases of its 16.3 d period. Some models predict that all such periodic repeating FRB have the same sign of temporal asymmetry, while others predict that sources with both signs are equally abundant. Future observations of other periodically modulated repeating FRB may distinguish among models on this basis.

Key words: radio continuum, transients: fast radio bursts, accretion, accretion discs, stars: binaries: close

1 INTRODUCTION
Observations of repeating Fast Radio Bursts (FRB) indicate temporal symmetry breaking on very different time scales:

- On times \( O(1 \text{ ms}) \) repeating FRB frequently show a “sad trombone” effect: during a burst, emission slides to lower frequencies. This is distinct from the source’s plasma dispersion (Pleunis et al. 2021; Bethapudi et al. 2022). No systematic “happy trombone” slide to higher frequencies has been observed in any FRB.
- On times \( O(1 \text{ d}) \) the periodically modulated activity of FRB 180916B (the only firmly confirmed periodic FRB, and the only one observed in detail) occurs at earlier phases of its 16.3 d period at higher frequencies than at lower frequencies. This was discovered at lower frequencies (Pastor-Marazuela et al. 2021; Pleunis et al. 2021) and Bethapudi et al. (2022) extended it to a third frequency band, suggesting a monotonic trend.

The extensive sky coverage of CHIME/FRB (CHIME/FRB Collaboration 2021) is rapidly increasing the number of known repeating FRB. The activity of some of these sources may be periodically modulated like that of FRB 180916B (there is no evident reason why this object should be exceptional), although insufficient data have yet been gathered to establish this. It will be determined whether all such sources have the same dependence of active phase on frequency, whether some sources show one sign of frequency dependence and others the other sign (and with what comparative abundance), or whether the activity phase of some periodic FRB is independent of the radio frequency of the observations.

The analogous question can be asked of “trombone” effects. There may already be sufficient data to establish that “sad trombones” are ubiquitous in repeating FRB, and that “happy trombones” may not occur at all.

2 SYMMETRY AND SYMMETRY BREAKING
Temporal symmetry breaking may distinguish among models of FRB behavior. For example, plasma refraction is greater at lower frequencies, so that lower frequency radiation follows a propagation path between plasma lenses that deviates from the straight line path of unrefracted radiation more than does higher frequency radiation. If there are plasma lenses on the propagation path then lower frequency radiation arrives later because of its greater path length, even if the lenses are thin and almost all the path is effectively in vacuum. If this effect is the cause of the frequency dependence of phases of periodically modulated FRB then their phases will be earlier at higher frequencies in every periodically modulated FRB source.

In contrast, if FRB, either individual pulses or the active window of periodic activity, result from the sweep of a beam or a beam envelope across the observer’s direction, then in the FRB population both senses of time dependence occur equally often because there is no preferred direction of sweep of a beam on the sky (or of the cross-product of its rotation vector with the direction to the observer). This applies to almost any observable, including polarization angle, variation of rotation measure, sawtooth intensity variation, etc.

Over the FRB population one sense of rapid (\( \sim 1 \text{ ms} \)) variation (the “sad trombone”) is preferred, excluding sweeping of a steady narrow beam across the observer’s direction as the origin of the bursts. No such statement can be made at present about the chromaticity of phase in periodically modulated FRB activity because it has been observed in only one source (Bethapudi et al. 2022).

An individual repeating FRB may show the same sense of temporal asymmetry in pulse after pulse, or (if periodically active) in active period after active period; a sawtooth pattern may sweep across the observer’s direction time and time again. In some models there is no relation between our direction and the direction of sweep through a sawtooth, so that some repeating FRB sources show systematically posi-
tive time-skewness $F(\tau)$, closely related to the bispectrum, of an observable $f(t)$ (Hasselmann, Munk & MacDonald 1963; Frenkel & Klebanoff 1967; Weisskopf et al. 1978)

$$F(\tau) \equiv \langle (f(t) - \langle f \rangle) \rangle^2 (f(t+\tau) - \langle f \rangle) \rangle^2\rangle$$

while other sources show $F(\tau)$ systematically negative.

Rotating beams with a sawtooth angular dependence are equally likely to have positive as negative time skewness if there is no preferred sense of rotation with respect to the beam pattern. This is plausible for slow rotation or precession of a compact object, but not necessarily for fast rotation that may influence the emission mechanism or if the rotation of the beam is produced by orbital motion that also determines the radiated power and spectrum.

In other models there is an intrinsic temporal asymmetry that all observers see; decaying eruptions are examples, consistent with the sad trombone effect. Once a sufficient number of repeating FRB with periodically modulated activity are observed, this test may distinguish among models. This is distinct from tests (Katz 2021) based on the rate of change of period of a single periodically modulated repeating FRB source.

3 REFRACTION

Plasma refraction (Er & Mao 2022; Zhu et al. 2022) is strongly chromatic, like the observed phase delays of FRB 180916B (Bethapudi et al. 2022). Plasma lensing may introduce frequency-dependent delays. This is analogous to plasma dispersion, but is not proportional to the dispersion measure. A thin lens far from the source may introduce delays as a result of differences between the lengths of ray paths, straight-line in the limit of high frequency and bent at lower, refracted, frequencies. These delays occur even if the rays propagate in vacuum outside thin lenses. They may be much greater than the dispersion delay of the lenses themselves.

The delay depends on the details of the lens geometry, but the characteristic angle of refraction

$$\theta = \mathcal{O}\left(\frac{\omega_p^2}{\omega^2}\right)$$

where $\omega_p$ is the plasma frequency and $\omega$ the frequency of the wave. Then the delay (Katz 2022a)

$$\Delta t = \mathcal{O}\left(\frac{D \omega_p^2}{2c \omega^2}\right)$$

where $D$ is the distance of the lens from the source (the possibility of such a lens close to the observer is excluded by the absence of such effects in other FRB or in Galactic pulsars). This form resembles that of the ordinary plasma dispersion delay but with the lens thickness $d$ replaced by $D$. If $D \gg d$ the bent path delay far exceeds the dispersive delay; to explain FRB 180916B this would have to be by a factor $\sim 10^5$.

The frequency scaling of Eq. 3 is contradicted in FRB 180916B by the observation (Bethapudi et al. 2022) that the exponent of $\omega$ is $-0.23 \pm 0.05$ rather than $-2$, and by the fact that plausible values of $\omega_p$ would imply implausibly large (outside any possible host galaxy) values of $D$. Alternative explanations must be sought for the frequency-dependent chromaticity of FRB 180916B.

4 MILLISECOND TIME SCALES

Many, if not all, bursts from repeating FRB show a drift to lower frequency distinct from the effect of plasma dispersion, the “sad trombone” effect (Michilli et al. 2018; Gajjar et al. 2018; CHIME/FRB Collaboration 2019; Hessels et al. 2019; Josephy et al. 2019; Pleunis et al. 2021; Bethapudi et al. 2022). None have shown a “happy trombone” (drift to higher frequency). This intrinsic property of bursts from repeating FRB excludes the possibility that their bursts are produced by the sweep of a narrow steady beam across the direction to the observer because that would be equally likely to produce upward drifts in frequency as downward drifts.

That hypothesis would also require that the opening angle of the beam $\theta \lesssim 2\pi \delta t/P$, where $\delta t$ is the burst width and $P$ the period of its rotation on the sky, presumably the observed period, which is 16.3 d for FRB 180916B. Then the Lorentz factor of the radiating particles would have to satisfy $\gamma \gtrsim 1/\theta \sim 10^8$, which would be difficult to reconcile with plausible accelerating mechanisms and losses by mechanisms such as Compton scattering. The dominance of sad trombones and the absence or rarity of happy trombones establishes that this behavior and the temporal structure and widths of bursts must be consequences of their radiation mechanism.

5 DAY TIME SCALES

Periods many orders of magnitude longer than burst durations may be attributed to motion of an envelope within which bursts may be directed. As argued in Sec. 2, in many, perhaps all, models, a particular source may be time-asymmetric and chromatic, and persistently so in the same sense of asymmetry, while the entire population of periodically modulated repeating FRB may, or may not, all have the same sense of time-asymmetry.

Here I suggest discriminating among models on the basis of whether they imply that all periodically modulated FRB have the same sense of time-asymmetric chromaticity. Discrimination would not be based on that sense, that is difficult to predict from models (other than the refractive model discarded in Sec. 3), but on the universality, or lack of universality, or a single sense.

5.1 Statistically Symmetric Models

In an intrinsically symmetric model a periodically modulated repeating FRB may have either sense of time asymmetry, and these occur with equal frequency in the FRB population. If we run a finger along the blades of saws oriented isotropically, we will feel gradually rising sawtooths followed by abrupt drops as often as the opposite. Astronomical examples include pulsar pulses if their underlying radiation pattern is stationary on the time scales of the pulses, and there is no preferred sense of rotation with respect to the angular radiation pattern. The beam pattern may be intrinsically skewed, like a sawtooth, but the rotation direction is equally likely to produce positive time-skewness as negative time-skewness.

Statistically symmetric models of periodically modulated FRB activity include precession (free or driven by external torques) of a rotating neutron star (Levin, Beloborodov & Bransgrove 2020; Li & Zanazzi 2021; Wei, Zhao & Wang...
and slow rotation of a neutron star (Beniamini, Wadiasingh & Metzger 2020; Li & Zanazzi 2021; Xu et al. 2022). These are statistically symmetric if, as expected, there is no preferential orientation of the precession or rotation rate vector with respect to the beam pattern.

5.2 Statistically Asymmetric Models

In a statistically asymmetric model one sense of time-asymmetric chromaticity is intrinsically preferred. Examples of statistically asymmetric phenomena include the motion of ratchets, the sounds of machine guns, earthquakes followed by aftershocks (but only rarely preceded by foreshocks, in contrast to the model (Katz 1986) now known as Self-Organized Criticality (Aschwanden 2011) in which the opposite is true) and, in astronomy, the repetitive outbursts of recurrent novae or Solar flares that rise abruptly but decay more gradually, reddening as they decay.

Statistically asymmetric models include those in which a compact object interacts with an accretion disc or a stellar wind because the beginning of such interaction (entry of the compact object or its beam into denser matter) is intrinsically different from its end (emergence from the denser matter), and orbital motion makes a compact object’s wake in a stellar wind lag behind, rather than advancing in front of, the compact object.

Such models have been developed by Ioka & Zhang (2020); Li et al. (2021); Wada, Ioka & Zhang (2021). Precessing accretion disc/jet models (Katz 2020, 2021, 2022b) may be intrinsically asymmetric because Newtonian mechanics makes the direction of precession opposite to that of the disc’s rotation, so that on one side of the accretion funnel the (slow) precession and (fast) rotational speeds add while on the other side they subtract. This may be confused by jitter around the mean precession, and it is unclear that the asymmetry of an accretional funnel (and jet, if there is one) is large enough to be significant. Lens-Thirring precession (Sridhar et al. 2021) is intrinsically asymmetric in the opposite sense because it is parallel to the disc’s angular momentum; in a binary this is expected to be aligned with the orbital angular momentum.

6 DISCUSSION

The large values of \( D \) implied by Eq. 3 imply that chromaticity on time scales of days must be intrinsic to the source rather than resulting from propagation delays. In the one known example, FRB 180916B, the mechanism that modulates its activity must break the symmetry between earlier and later phases of activity.

When more periodically modulated FRB sources are observed it will be possible to distinguish statistically symmetric models in which the sign of the exponent of the variation of phase with frequency is equally likely to be either positive or negative from statistically asymmetric models in which it must be negative, as observed in FRB 180916B (models in which it can only be positive are excluded by that one source). Several suggested models appear to have been excluded even by the extant data (Wei, Zhao & Wang 2022).

DATA AVAILABILITY STATEMENT

This theoretical study did not obtain any new data.

ACKNOWLEDGEMENT

It is an honor to acknowledge a long-ago discussion with the late oceanographer Walter Munk in which he called my attention to Hasselmann, Munk & MacDonald (1963).

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