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Repeating fast radio bursts reveal the secret of pulsar magnetospheric activity

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Abstract

The puzzling mechanism of coherent radio emission remains unknown, but fortunately, repeating fast radio bursts (FRBs) provide a precious opportunity, with extremely bright subpulses created in a clear and vacuum-like pulsar magnetosphere. FRBs are millisecond-duration signals that are highly dispersed at distant galaxies but with uncertain physical origin(s). Coherent curvature radiation by bunches has already been proposed for repeating FRBs. The charged particles are created during central star's quakes, which can form bunches streaming out along curved magnetic field lines, so as to trigger FRBs. The nature of narrow-band radiation with time-frequency drifting can be a natural consequence that bunches could be observed at different times with different curvatures. Additionally, high linear-polarization can be seen if the line of sight is confined to the beam angle, whereas the emission could be highly circular-polarized if off-beam. It is also discussed that pulsar surface may be full of small hills (i.e., zits) which would help producing bulk of energetic bunches for repeating FRBs as well as for rotation-powered pulsars.

KEYWORDS

dense matter, elementary particles, neutron star, pulsar

1 | INTRODUCTION

It has been over half a century since the discovery of pulsars (e.g., Manchester 2017), but the underlying mechanism responsible for pulsar coherent radio emission is still a matter of debate. This radiative mechanism depends on the production, acceleration, and radiation of electron-positron ($e^{\pm}$) pair plasma in pulsar magnetosphere, and certainly we have known a lot about what happens: the kinematic spin-energy of a pulsar is lost dominantly by the current flow in its nearby magnetosphere (Contopoulos & Spitkovsky 2006; Goldreich & Julian 1969); $e^{\pm}$-pairs are produced and accelerated in so-called gaps, in the mainstream, either inner-vacuum gap just above pulsar surface (Ruderman & Sutherland 1975) or slot gap with space charge-limited flow (Arons & Scharlemann 1979) and even outer-vacuum gap (Cheng et al. 1986), to be relevant to the binding energy of charged particles on the surface. Nonetheless, in a view point of global current flow, the conventional open-field line region could be divided into annular and core sectors (Qiao et al. 2004), both of which may contribute pair plasma and thus coherent radiation. In order to understand the non-stationary $e^{\pm}$-production plasma that flows out non-homogeneously (Usov 2002), numerical methods with high resolution are applied to solve the mysterious pulsar radiation problem (e.g., Timokhin 2006), with extending the simulations to 2D (Philippov et al. 2020). Despite these successes, it is worth noting that the magnetospheric activity should be subjected to the nature of pulsar surface, which is related to the big question of pulsar inner structure (i.e., the equation of state of supra-nuclear matter at low temperature), a more challenging problem in today's physics and astrophysics!

It has a long history to think philosophically bulk strong matter (Lai et al. 2023b), i.e., "*gigantic nucleus*" in Landau's words presented just in the late age of developing quantum mechanics (Landau 1932). Now it is well known that pulsar-like compact stars are such objects in reality, but unfortunately/fortunately, the nature of pulsars has remained still a mystery even after more than 90 years (Xu 2023), supposed to be the first big one to be solved in the era of gravitational-wave astronomy. The pulsar matter could be extremely isospin-unsymmetrical so that normal baryonic crust would be necessary to cover (i.e., normal neutron star model), but could also probably consist of 2- or 3-flavored itinerant quarks (i.e., quark star model). In view of charge and flavor symmetries of light quarks (up, down, and strange) and no-perturbativity of the fundamental strong interaction at pressure free and at zero temperature, it is proposed that the building blocks of pulsar matter could be "*strangeons*", an analogy of atomic nucleons but with negative strangeness (Lai & Xu 2017; Xu 2003). This strangeon star model could be successful in explaining, such as massive pulsars and low tidal deformability (Lai et al. 2019), the spin-irregularity of glitches (e.g., Lai et al. 2023b), and huge free energy for bursts and flares (Chen et al. 2023; Xu et al. 2006), and we are concerning here about its implications to pulsar magnetospheric activity.

Two immediate consequences of strangeon matter on pulsar surface should be of "miser" and "zits". (1) *Miser*. A bare strangeon star looks like "a miser" because both positively and negatively charged particles can hardly be extracted from the surface so that an inner-vacuum gap works naturally there (Xu et al. 1999; Yu & Xu 2011). (2) *Zits*. Although the interactions between nucleons and strangeons could both be "Van der Waals"-like, a straneon is more akin to a classical particle than quantum wave due to its high mass, $m_{\rm st}$, as indicated by its Compton wavelength of $\lambda \simeq \hbar/(m_{\rm st}c)$. It was then conjectured that condensed strangeon-matter could be in a classical solid state (Xu 2003), and a bare strangeon star surface may have small hills (i.e., "zits") where the induced electric fields parallel to magnetic field-lines should be remarkably stronger than that anywhere else. Nonetheless, how can we find any clues to the strangeon surface? The booming research on fast radio bursts (FRBs) could be one of the examples.

In short, FRBs are bright radio transients prevailing in the universe with milli-second duration. The field has witnessed a rapid increase in the frontiers of observations and theories since the first FRB discovery (Lorimer et al. 2007). Without doubt, the key issue in the field is to understand FRB's radiative mechanism and further the underlying physics relevant to FRB's central engine.

FRB sources can fall into two groups: repeaters and apparently non-repeating ones. However, whether all FRBs can repeat is still an open question even the two groups show some noticeable differences in the burst morphology (Pleunis et al. 2021). The sources are thought to be cosmological origin due to their dispersion measures (DMs) in excess of the Galactic values, and it was confirmed after the first repeater was localized in its host galaxy (Bassa et al. 2017; Chatterjee et al. 2017; Marcote et al. 2017). Besides, an FRB-like burst was found in a Galactic compact star (soft gamma ray repeater, SGR), so-called "magnetar" (Bochenek et al. 2020; CHIME/FRB Collaboration et al. 2020), which is named as SGR J1935+2154, and the burst is temporally associated with an X-ray burst (Li et al. 2021; Ridnaia et al. 2021; Tavani et al. 2021). This discovery suggests that at least some FRBs could be created by extragalactic magnetars. That is not surprising as pulsed radio emission, thought much weaker, are sometimes detected from these objects after out-bursts, for example, the fifth radio-loud Galactic magnetar Swift J1818.0-1607 (Esposito et al. 2020).

Some intriguing properties have been found in repeating FRBs which are surely meaningful to study their origin. For instance, the "sad trombone" spectral structure, that is, subpulses with higher frequency arrive earlier than those with lower frequencies, has been found in some repeating FRBs (e.g., Hessels et al. 2019). Careful polarization measurements can give more physical information about their magnetospheric origin. In general, most bursts are dominated by linear polarization (LP) and present a flat polarization position angle (PA) across each pulse, but there are also some bursts that have circular polarization (CP) fractions larger than 50% and even up to 75% (Xu et al. 2022). FRB 180301, a repeater, exhibits varying PAs across the burst envelope (Luo et al. 2020), which is reminiscent of an S-shaped PA across the burst envelope of a pulsar. All these might reveal the underlying mechanism of coherent radio emission in pulsar magnetosphere, and a strangeon matter surface could even be needed.

In this paper, we review the trigger and radiation mechanism of repeating FRBs. In Section 2, we focus on starquake as the trigger mechanism. In Section 3, we demonstrate that the drifting pattern and the variety of radio polarization (both linear and circular) can be well understood within the frame work of coherent curvature radiation by bunches. In Section 4, high-tension point discharge at "zits" on a strangeon surface is discussed. We summarize our results in Section 5.

2 | QUAKE-INDUCED REPEATING FRBS?

Quakes could occur in pulsar-like compact objects, either for normal neutron stars (magnetras) with ultra-strong magnetic fields when the internal magnetic field exceeds a threshold stress, or for strangeon stars when slow elastic loading develops to a critical point so as to release unstably. An FRB could be triggered by a quake, though no final conclusion is obtained about the free energy: magnetic energy for magnetars or elastic/gravitational energy for strangeon stars. Both processes may let a lot of energy release from the central star into the magnetosphere so that charged particles are then accelerated and stream out along the magnetic field lines.

From the statistical side, nonlinear dissipative systems can show self-organized criticality (SOC) behaviors (Aschwanden 2011). The star whether a pulsar-like compact star or the Earth, can build up stresses that make the crust crack and adjust the stellar shape in order to reduce its deformation. It is then expected that pulsar-like compact star activities (e.g., magnetar quake) may exhibit characteristics of self-organized criticality, as has been observed in earthquakes. Quakes from pulsar-like compact stars can share similar properties with earthquakes.

In 2017, 14 bursts above the threshold of 10 sigma were detected by Breakthrough Listen Digital Backend with the C-band receiver at the Green Bank Telescope (Gajjar et al. 2017). We found that the burst sequence exhibits some earthquake-like behaviors such as the power-law burst energy distribution, which is reminiscent of the Gutenberg-Richter law, a typical Earthquake behavior (Wang et al. 2018; Wang and Zhang 2019; Wang & Yu 2017). The temporal behavior of the burst sequence satisfies the Omori law, which interprets the time decay of the seismicity rates of an aftershock sequence. The timescale for this process is $\sim L/v_A \approx 1-10$ ms, where L is the scale of the reconnection-unstable zone and v_A is the Alfvén velocity. The $e^{\pm}$-pair production is excited during the starquake, and electrons or positions (as a leading charge in the following discussion) are suddenly accelerated to ultra-relativistic velocity, creating coherent radio emissions. The high burst rates by plate collisions in central star's crusts could be consistent with the observation of FRB 20121102A, with maximum value reaching $122\,h^{-1}$ (Li et al. 2022).

3 | COHERENT CURVATURE RADIATION BY MAGNETOSPHERIC BUNCHES

For FRBs, an extremely coherent radiation mechanism is required to explain the high brightness temperature. The trajectories of charged particles are tracked by magnetic field lines because the vertical momentum perpendicular to the field line damps very fast. Curvature radiation can be created by the streaming charged bunches.

Charged bunches can be formed if their sizes are smaller than the half wavelength of the emission so that the luminosity is proportional to N_e^2 rather than N_e, where N_e is the number of charges inside the bunch. The flux of curvature radiation is peaked at $\nu_c = 3c\gamma^3/(4\pi\rho) = 0.7\gamma_2^3\rho_7^{-1}$ GHz, where γ is the Lorentz factor of bunches, c is the speed of light, and ρ is the curvature radius. In order to match the observed FRB frequency, the emission region should be from several tens to several hundred stellar radii with a required Lorentz factor in order of several hundreds. An FRB can be seen when the line of sight (LOS) sweeps across the field lines where the bunches appear coincidentally.

If one can observe two or more separated bulk of bunches, there would be two or more sub-pulses. We assume that the emitting two bulks are generated at the same time so that the observed time interval of subpulses is mainly caused by the geometric delay. By considering an axisymmetric magnetic configuration, one can obtain the geometric time delay for emissions from two bulk of bunches:

$$\Delta t_{\rm geo} \simeq \frac{\Delta r}{c}\left[\left(1+\frac{1}{2\gamma^2}\right)I_n(\theta) - \cos\theta_p\right], \tag{1}$$

where Δr denotes the distance between the points where emission can sweep the LOS at two magnetic field lines and n denotes magnetic configuration ($n=1$ for dipole) (Wang et al. 2022d). Here the subscript “1” denotes the bulk at lower height and “2” for at higher height. The result of equation (1) is always positive independent with magnetic configuration of n. Therefore, the pulses seen later travel farther into the less-curved part of the magnetic field lines, thus emitting at lower frequencies, matching the observed downward drifting pattern (Wang et al. 2019).

The observed amplitude can be demonstrated by the summation of the curvature radiation amplitude of individual particles since FRB emissions are coherent. Basically, $A_\parallel$ and $A_\perp$ are defined as two orthogonal polarized components of the amplitude along $\boldsymbol{\epsilon}_\parallel$ and $\boldsymbol{\epsilon}_\perp$, where $\boldsymbol{\epsilon}_\parallel$ is the unit vector pointing to the center of the instantaneous circle, and $\boldsymbol{\epsilon}_\perp = \boldsymbol{n}\times\boldsymbol{\epsilon}_\parallel$ is defined (Jackson 1998). The two amplitudes of the bunch are the summation of individual particles which are given by

$$A_\parallel \simeq \frac{i2}{\sqrt{3}}\frac{\rho}{c}\left(\frac{1}{\gamma^2}+\varphi^2+\chi^2\right)K_{\frac{2}{3}}(\xi)$$

$$+\frac{2}{\sqrt{3}}\frac{\rho}{c}\chi\left(\frac{1}{\gamma^2}+\varphi^2+\chi^2\right)^{1/2}K_{\frac{1}{3}}(\xi), \qquad (2)$$

$$A_\perp \simeq \frac{2}{\sqrt{3}}\frac{\rho}{c}\varphi\left(\frac{1}{\gamma^2}+\varphi^2+\chi^2\right)^{1/2}K_{\frac{1}{3}}(\xi),$$

where χ is the angle between the considered trajectory and trajectory at $t = 0$, φ is the angle between the LOS and trajectory plane, and K_ν is the modified Bessel function.

According to Equation (2), we consider three cases with different bunch scales ($\varphi_t = 0.1/\gamma$, $\varphi_t = 1/\gamma$, $\varphi_t = 10/\gamma$, where φ_t is the half opening angle of bunch). The polarization profiles across the burst envelope are plotted in Figure 1. Let us define that the LOS is confined to the radiation beam as on-beam, whereas off-beam. The beam angle for a bunch is defined as $\theta_b = \varphi_t + \theta_c$, where θ_c is spread angle of emission for single charge (Wang et al. 2022a). Emission from an ultrarelativistic particle is mainly confined in a conal region (spread angle). The spread angle for curvature radiation of a single charge is $1/\gamma$ when $\nu = \nu_c$.

As shown in Figure 1, emissions for all three cases have high LP fractions if the LOS is inside the beam (on-beam), and the CP fraction becomes significant when the LOS is off-beam. Waves are of left-CP at $\phi < 0$ but change to right-CP after the LOS sweeps across the central axis of the bunch. For the on-beam case, there is a large phase space where the summation of $A_\perp$ cancels out so that the emission has roughly 100%-LP fraction. In a word, the emission can only become highly circular polarized for the off-beam cases.

Additionally, we investigate two propagation scenarios, including Faraday conversion and absorption in closed field line region. Faraday conversion appears at a magnetized plasma medium which has B component perpendicular to the LOS. Conversion between LP and CP can be seen due to the difference in group velocity between O mode and X mode photons. However, the LP and CP fractions oscillate with λ^3 inconsistent with the observation of λ^2-oscillation in FRB 20201124A. Outcome emissions with a high CP still need the income waves to have large CP fractions (Wang et al. 2022b). Another scenario is the absorption effect. Right CP waves are likely to be optically thick for a rapidly rotating neutron star with a strong magnetic field (Lu et al. 2021). Emissions with highly LP fractions are required to be emitted from at least higher than the absorption region, leading to a time delay between LP and CP bursts.

4 | “ZITS” ON PULSAR’S SURFACE?

It is multi-motivated to study mountain building of solid strangeon stars (Yang & Xu 2011), and the maximum height, $h_{\rm max}$, of mountains on strangeon star surface could be estimated by an order-of-magnitude calculation with $\mu \sim \rho g h_{\rm max}$,

$$h_{\rm max} \sim (7\times10^2\ {\rm cm})\ \mu_{32}\rho_{15}^{-1}M_1^{-1}R_6^2, \qquad (3)$$

where $\mu = (10^{32}\ {\rm ergs\ cm^{-3}})\ \mu_{32}$ is the shear modulus, $\rho = (10^{15}\ {\rm g\ cm^{-3}})\ \rho_{15}$ is the surface density, and the mass and radius are, $M = M_\odot\ M_1$ and $R = (10^6\ {\rm cm})\ R_6$, respectively. Soon after core-collapse supernova, a hot strangeon star should be in a liquid state at temperate of a few 10 MeV (Dai et al. 2011; Xu & Liang 2009; Yuan et al. 2017), but it would be solidified at temperate of a few 0.1 MeV less than hours. Initially, the surface should be slippery after quenching of liquid-solid phase transition, and the landscape may comprehend rolling country and plains, with differences of vertical altitude $< h_{\rm max}$. However, the surface of an aged strangeon star could be full of small hills (i.e., “zits”-like, depicted in Figure 2), especially in the polar cap region, due to the bombardment of TeV-e^+/e^+ on the polar cap, with the kinematic energy in the center of mass of $\gtrsim$ GeV (Xu & Qiao 2000). Frankly speaking,

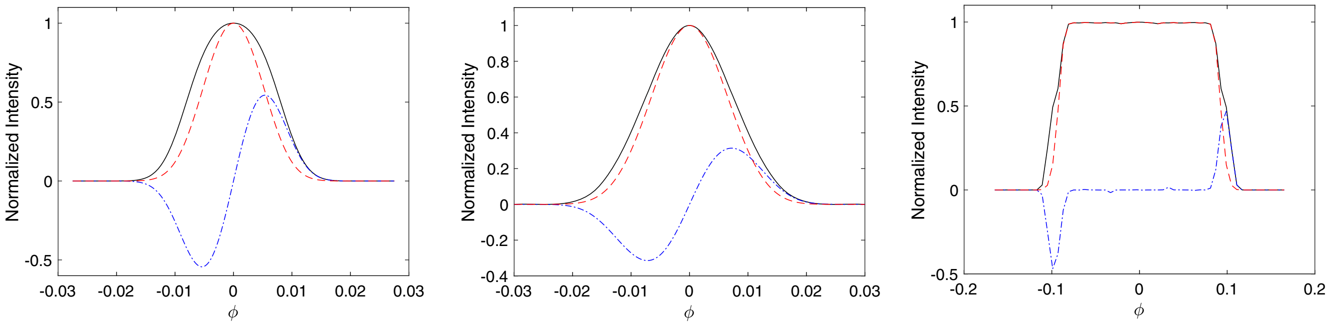

FIGURE 1 Simulated polarization profile and PA across the burst envelope for different frequencies: (a) $\varphi_t = 0.1/\gamma$; (b) $\varphi_t = 1/\gamma$; (c) $\varphi_t = 10/\gamma$. The Normalized intensities are plotted in black solid lines. The LP fractions are plotted in red dashed lines. The CP fractions are plotted in blue dotted-dashed lines.

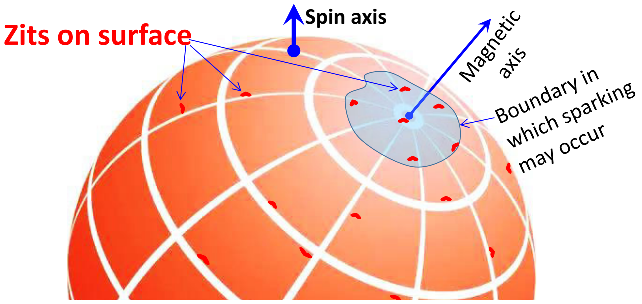

FIGURE 2 A bare strangeon star should not have a smooth surface, but be covered with pimples, that is the zits illustrated here. These small hills on pulsar surface might be responsible for the magnetospheric activity relevant to coherent radio emission.

strangeon star-quake to be responsible for pulsar glitch observed (e.g., Lai et al. 2023b) would additionally be a strong pressed orogenic movement to create zits. It is worth noting that the strong zits[1] on strangeon matter surface would keep a long time, while the electromagnetic zits on naked neutron star (e.g., Gil et al. 2003; Mitra et al. 2023; Turolla et al. 2004) surface could hardly stand up against the collisions of TeV-$e^{\pm}$ pairs.

It is well known that $e^{\pm}$-pairs are accelerated and produced by the spin-induced electric fields, $E_{||}$, which could be too weak to be active for slow and low-magnetic field pulsar, but $E_{||}$-field could be enhanced by $(10-10^3)$ times at the peak of hill, so-called point-discharging. This may imply that the inner-vacuum gap sparking occurs regularly in "rolling country and plain" regions (manifested as ordered sub-pulse drifting), but has priority to happen irregularly around zits. Alternatively, regular and irregular sub-pulse drifting might be the result of quasi-periodic discharging around several zits. In this picture, it is very natural for $e^{\pm}$-pairs plasma to flow out nonstationarily and inhomogeneously in case of the point discharges. This could be good news for coherent radio emission of pulsar (Usov 2002).

Observational facts may hint at the existence of zits on pulsar's face. A single pulse observation with China's FAST could be evidence for a rough surface of PSR B2016+28 via the detection that the modulation period along pulse series is positively correlated to the separation between two adjacent sub-pulses (Lu et al. 2019) as higher $E_{||}$ would lead to faster drifting of sub-pulses. The unusual arc-like structure of the bright pulsar PSR B0329+54 (Mitra et al. 2007), that is, the distinct core-weak patterns (Wang et al. 2023a), might result from the suppression of "core"-sparking by point discharge at zits outside the core. Recently, the asymmetric sparking points located away from the magnetic pole of the the whole-pulse-phase pulsar PSR B0950+08 (Wang et al. 2022c), as revealed by the polarization measurements of both integrated and single pulse profiles (Wang et al. 2023b), would be new evidence for zits on a strangeon's face. Certainly, further studies of radio singe pulses, especially with the highly-sensitive FAST, are surely welcome to find solid evidence for zits on face.

What is the magnetospheric difference between regular pulsars and repeating FRBs if pulsar-like compact stars are responsible for both kinds of the extremely coherent radio emission? The essential difference may arise from the fact that regular pulsars are basically rotation-powered, while repeating FRBs could probably be powered by a stellar activity via either a starquake or magnetic re-connection near the surface, both being able to contribute mountain-building movement. An FRB object is usually below the deathline at ordinary times, exhibiting a vacuum-like clean magnetosphere, but $e^{\pm}$-plasma can occasionally erupt from the star through sparking around zits during an active period. This may result in a higher coherence and thus a bright emission of FRBs.

5 | SUMMARY

Pulsar-like compact objects are exceptionally focused in the era of multi-messenger astronomy, with two mysteries to be solved: the radiative mechanism of coherent radio emission and the equation of state of cold matter at supra-nuclear density, both studies of which have a very long history. It is explained that these two problems could be internally related: the analysis of radiation features could play an important role in revealing the surface of central star and thus the nature of dense matter. We propose that, because of the high rigidity of strangeon matter, pulsar surface may be full of small hills (i.e., zits) which would help producing bulk of energetic bunches for repeating FRBs as well as for rotation-powered pulsars. More observational examinations should be carried out in order to clarify the issues of whether pulsars are neutrons or strangeon stars.

Even though there are hundreds of FRB sources have been discovered and dozens of them can repeat the physical origin(s) of FRBs are still unknown. We review that coherent curvature radiation by bunches as the radiation mechanism for repeating FRBs. The spectra-temporal pulse-to-pulse properties can be well understood within the framework of curvature radiation. A downward drifting pattern is a natural consequence that bulks observed at an earlier time were always emitted in a more-curved part of field line.

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[1] The typical height of zits could be $\sim (10^{-3}-10^{-1})h_{\max}$, that is, several millimeters to decimeters, by the experience of comparing mountain peaks and the Himalayas on the Earth.

FRBs can exhibit a wide variety of polarization properties, not only between sources but also from burst to burst for a same one. Within the coherent curvature radiation, high LP would appear when the line of sight is inside the emission beam (the on-beam case), whereas no-zero high CP would be presented when it is outside (the off-beam case). By considering the bulk shape and pulsar's spin, one can only observe part of beam so that a wide variety of polarization can be detected (Wang et al. 2022b). Cyclotron resonance as a propagation effect can result in the absorption of one CP mode photons at a low altitude region of the magnetosphere, and a circularized FRB should thus be emitted from a high-altitude region. Faraday conversion can produce CP with Stokes parameters oscillation, but the mean CP depends only on the income wave.

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