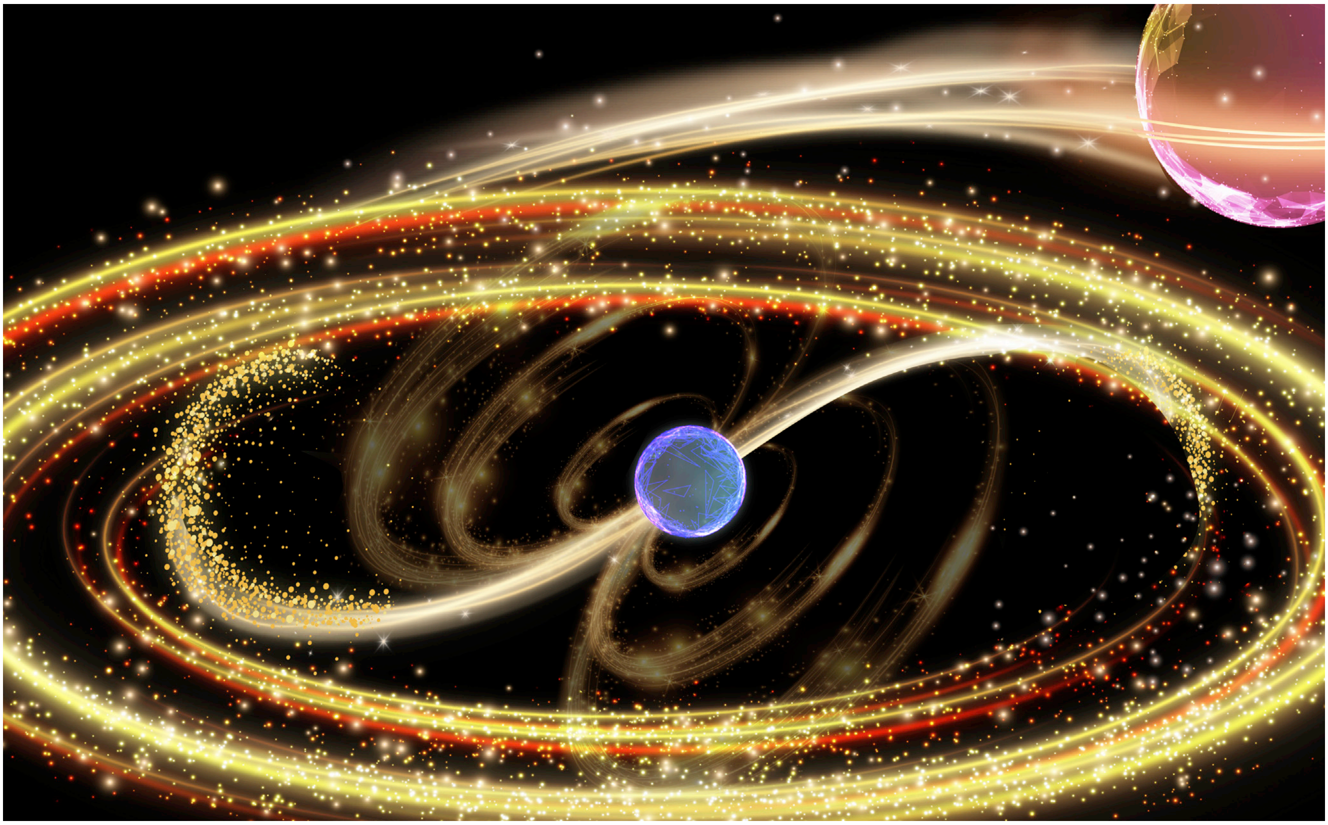
Report

Repeating fast radio bursts from collapses of the crust of a strange star

Jinjun Geng,[1,*] **Bing Li,**[2,3] **and Yongfeng Huang**[4,5,*]
*Correspondence: jjgeng@pmo.ac.cn (J.G.); hyf@nju.edu.cn (Y.H.)

Received: March 16, 2021; Accepted: August 9, 2021; Published Online: August 12, 2021; https://doi.org/10.1016/j.xinn.2021.100152

Graphical abstract



Public summary

- Strange quark stars are extremely compact objects mainly composed of u, d, and s quarks
- Fractional collapse of the crust of a strange quark star can explain the repeating FRB 180916
- Materials accreted from the companion star accumulate at the polar region and trigger the local collapse
- The 16-day periodicity of FRB 180916 originates from the thermal-viscous instability of the accretion disk, and the active window corresponds to a high accretion state of the system

Repeating fast radio bursts from collapses of the crust of a strange star

Jinjun Geng,[1,*] Bing Li,[2,3] and Yongfeng Huang[4,5,*]
[1]Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, China
[2]Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[3]Particle Astrophysics Division, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[4]School of Astronomy and Space Science, Nanjing University, Nanjing 210023, China
[5]Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210023, China
*Correspondence: jjgeng@pmo.ac.cn (J.G.); hyf@nju.edu.cn (Y.H.)

Received: March 16, 2021; Accepted: August 9, 2021; Published Online: August 12, 2021; https://doi.org/10.1016/j.xinn.2021.100152

Citation: Geng J., Li B., and Huang Y. (2021). Repeating fast radio bursts from collapses of the crust of a strange star. The Innovation **2(4)**, 100152.

Strange stars (SSs) are compact objects made of deconfined quarks. It is hard to distinguish SSs from neutron stars as a thin crust composed of normal hadronic matter may exist and obscure the whole surface of the SS. Here we suggest that the intriguing repeating fast radio bursts (FRBs) are produced by the intermittent fractional collapses of the crust of an SS induced by refilling of materials accreted from its low-mass companion. The periodic/sporadic/clustered temporal behaviors of FRBs could be well understood in our scenario. Especially, the periodicity is attributed to the modulation of accretion rate through the disk instabilities. To account for a ~16-day periodicity of the repeating FRB source of 180916.J0158+65, a Shakura-Sunyaev disk with a viscosity parameter of 0.004 and an accretion rate of 3×10^{16} g s^{-1} is invoked. Our scenario, if favored by future observations, will serve as indirect evidence for the strange quark matter hypothesis.

Keywords: **accretion; compact objects; radio bursts; degenerate matter; low-mass X-ray binary stars**

INTRODUCTION

Fast radio bursts (FRBs) are short (duration of milliseconds) radio bursts that remain mysterious. Their high brightness temperature makes astrophysicists believe that the radio pulse originates from the so-called coherent emission like the radio pulsar does,[1,2] although details for such collective radio emissions are still unclear.[3,4] Since the first discovery,[5] rapid progress has been made in the FRB field. Along with the increasing FRB number, it was found that some of them are individual events, i.e., do not repeat within a monitor period, while some sources are obviously repeating.[6]

The majority of repeating FRBs have been observed to appear sporadically (e.g., FRB 121102[7]). Recently, it has been found that the repeating FRB source 180916.J0158+65 (FRB 180916) shows a $\sim$16-day periodicity, within which the bursts gather in a 5-day active window.[8] Besides, detection of tentative periodic behavior ($\sim$160 days) of FRB 121102 over 5 years of data is reported,[9] although bursts from FRB 121102 were previously thought to be clustered without a regular pattern. Several scenarios have been proposed to explain the periodicity; e.g., the orbital motion of the FRB source,[10–14] long-lived precession of the emitting region,[15,16] and the ultralong rotational periods of the bursting source.[17] However, there is still no consensus on the cause of the periodicity. An extremely high eccentricity ($e > 0.95$) is required if the periodicity and the active window come from the pure binary orbital modulation.[12] Moreover, it is suggested that theories where the FRB periodicity arises from forced precession of a magnetar by a companion or fallback disk are not favored by analyzing the chromatic active window of FRB 180916.[18,19]

Putting aside the question of whether repeating and non-repeating bursts come from the same kind of sources/processes or are simply due to observational bias, it is urgent to establish a physical scenario that could naturally account for most characteristics of repeating FRBs. The coincidence of FRB 200428 and soft gamma-ray repeater 1935+2154 strongly supports that magnetars are the sources of at least some FRBs.[20] Motivated by the reasonable explanation for FRB 200428 through the instant accretion onto the magnetar,[21] we invoke a similar compact object in a binary system to explain the periodic FRB.

RESULTS AND DISCUSSION

Collapse of crust

Strange quark matter may be the true ground state of hadronic matter,[22] from which strange stars (SSs), made of deconfined u, d, and s quarks, are predicted. A thin crust composed of normal hadronic matter may exist and obscure the whole surface of the SS.[23] A typical SS with a mass of 1.4 solar mass ($M_{\odot}$) cannot have a crust more massive than $M_{\rm th} \sim 3.4 \times 10^{-6} M_{\odot}$ with a thickness of $\Delta \sim 10^4$ cm and a bottom density of 8.3×10^{10} g cm^{-3} (see section "methods").

Like the neutron star (NS) in the low-mass X-ray binary (LMXB), we consider an SS in a binary with a K or M dwarf companion, or a white dwarf companion. When materials from the companion's Roche lobe are accreted, a disk around the SS is formed. As the material gets much closer to the SS, the magnetic field begins to exert significant influence on the inflow at the so-called Alfvén radius. Within the Alfvén radius, the material is expected to flow along field lines onto the polar cap region of the SS (Figure 1). Whenever the crust mass exceeds $M_{\rm th}$ or the bottom density exceeds the threshold value, the crust will collapse. Since the mass inflow may be elongated tongue-like[24] and the diffusion timescale is much longer than the free-fall timescale, only a fraction of the crust near the footprint of these field lines will collapse (see section "methods"). During each fractional collapse, the sustaining electric field at the crust bottom will be turned off due to the screening of the electron-positron (e^+e^-) pairs from the increasingly heated SS surface (see below), which will last until the outgoing energy flux is high enough to push away the rest of the upper crust matter. Materials from the surrounding disk can continuously refill the crust, which results in repeating fractional collapses. We argue that this scenario could naturally explain the repeating FRBs.

Assuming the collapse to be a free-fall process, the collapse timescale $\sqrt{3\pi/(32G\rho_{\rm SS})}$ is much less than 1 ms, where $\rho_{\rm SS} \approx 10^{14}$ g cm^{-3} is the average density of the SS. Two kinds of energy, gravitational energy and deconfinement energy, are released after the collapse. We take the energy rate as $\sim$6.3 MeV per nucleon[25,26] in our following estimates. For a typical FRB of isotropic energy of $E_{\rm iso} \sim 10^{40}$ erg, the ratio between the required fallen mass δM and the crust mass is $\delta M / M_{\rm th} \sim 10^{-10} f_{\rm b,-3} E_{\rm iso,40}$, where $f_{\rm b}$ is the beaming factor of the FRB. The convention $Q_x = Q/10^x$ in cgs units is adopted hereafter unless specifically stated. This means that the crust is an ideal energy reservoir for frequent repeating FRBs.

Usov discussed bare SSs and found that for electromagnetic waves propagating in the hot strange quark matter, only high-frequency photons (>18.5 MeV) could be efficiently emitted[27,28]; i.e., the bare SS surface is

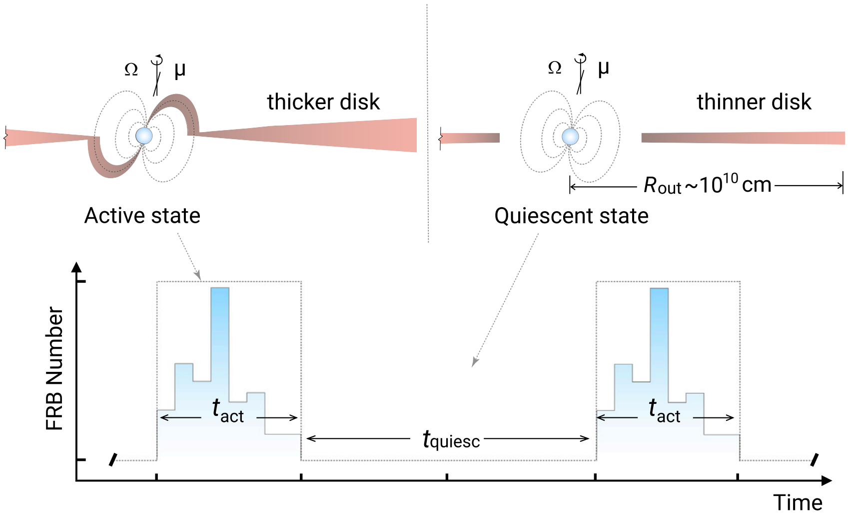


Figure 1. Schematic illustration of periodic repeating FRBs in the SS crust collapse scenario The active window and the quiescent phase of repeating FRBs correspond to different states of the accreting disk driven by the thermal-viscous instability. When the accretion rate is relatively low, the Alfvén radius is large and the accretion system is in the propeller regime, which corresponds to the quiescence phase of repeating FRBs since almost no materials will be accreted onto the SS. In a state of enhanced accretion rate triggered by rapid change in opacity associated with the ionization of disk materials, the system enters the active phase, and repeating FRBs are produced due to the continuous accretion onto the crust of the SS.

very dim in X-rays. It was thus pointed out that the emission from the heated SS surface should be dominated by the e^+e^- pairs created in an extremely strong electric field at the surface. The flux of e^+e^- pairs from unit SS surface is estimated as[28]

$$\dot{n}_\pm \cong 10^{39}\left(\frac{T_{\rm s}}{10^9\ {\rm K}}\right)^3 \exp\left[-11.9\left(\frac{T_{\rm s}}{10^9\ {\rm K}}\right)^{-1}\right]\ {\rm s}^{-1}{\rm cm}^{-2}, \qquad \text{(Equation 1)}$$

where $T_{\rm s}$ is the surface temperature of SS. Its corresponding energy flux per unit surface is $F_\pm = (m_e c^2 + k_{\rm b} T_{\rm s})\dot{n}_\pm$, where m_e is the electron mass, c is the speed of light, and k_b is the Boltzmann constant. However, due to the extremely high pair density, the pairs will annihilate into photons, which results in a photon-lepton fireball streaming out along the narrow tunnel of the crust. The timescale $t_{\rm ann} \sim (\dot{n}_\pm \sigma_{\rm T})^{-1}$ for annihilation of e^+e^- pairs is much shorter than the escaping timescale $t_{\rm esc} \sim \Delta/c$, i.e., $t_{\rm ann}/t_{\rm esc} \le 10^{-4}$for $T_{\rm s} \ge 10^9$ K, where σ_T is the Thomson cross section. Like a bullet in a gun barrel, e^+e^- pairs will be accelerated by the radiation pressure. Denoting the number density of e^+e^- pairs as $n_\pm$, the mean free path of these pairs is written as $(n_\pm \sigma_{\rm T})^{-1}$. Considering that the mean free path may be of order Δ for the pairs to escape, we could obtain the density of pairs as $n_\pm \approx (\Delta\sigma_{\rm T})^{-1}$ when they break out from the crust. Assuming $F_\pm$ is fully converted into kinetic energy of the pairs, the bulk Lorentz factor of the escaping pairs is estimated to be $\gamma_\pm \cong \sigma_{\rm T}\Delta F_\pm/(m_e c^3)$. Accurate heat transfer calculation gives that $T_{\rm s}$ is $\sim 10^9$ K within 10 ms after the crust collapses,[29] which means that the typical value of $\gamma_\pm$ is ≈ 2000. As shown in the section "methods," this relativistic e^+e^- flow could account for the coherent emission of FRBs.

Periodic/sporadic/clustered behavior of FRBs

The $\sim$16-day periodicity of FRB 180916 consists of an active duration of $t_{\rm act} \approx 5$ days and a quiescence duration of $t_{\rm quiesc} \approx 11$ days. In our model, both timescales could be understood by the well-known cycle of the accretion disk driven by the thermal-viscous instability (Figure 1). The standard thin disk is thermally (and viscously) unstable for a disk temperature of $\sim 10^4$ K due to rapid change in opacity associated with the ionization of hydrogen atoms. A well-defined duty cycle of low/high accretion state is expected from this instability, and is often invoked for periodic outbursts in LMXB transient systems.[30]

During the active window, an enhanced accretion rate of $\dot{M}_{\rm act} \cong 10^{18}$ g s^{-1} (equivalent to $10^{-8} M_\odot$ year^{-1}) onto the SS is required to repeatedly produce FRBs on the timescale of seconds. Assuming a Shakura-Sunyaev disk[31] with a total mass of $M_{\rm disk} = 2\pi\int_{R_{\rm in}}^{R_{\rm out}} R\,\Sigma\,dR$, then the duration of the high accretion state could be estimated by the depletion timescale of the disk, i.e.,

$$t_{\rm act} = \frac{M_{\rm disk}}{\dot{M}_{\rm act}} \approx 1.3\left(\frac{\alpha}{0.01}\right)^{-\frac{4}{5}}\left(\frac{\dot{M}}{10^{16}\ {\rm g\ s^{-1}}}\right)^{\frac{7}{10}}\left(\frac{\dot{M}_{\rm act}}{10^{18}\ {\rm g\ s^{-1}}}\right)^{-1} \times\left(\frac{M_{\rm SS}}{1.4M_\odot}\right)^{\frac{1}{4}}\left(\frac{R_{\rm out}}{10^{10}{\rm cm}}\right)^{\frac{5}{4}}{\rm days}, \qquad \text{(Equation 2)}$$

where α is the prescription parameter for the viscosity, Σ is the surface density, $\dot{M}$ is the constant disk accretion rate in the low state, $M_{\rm SS}$ is the SS mass, and $R_{\rm out}$ is the outer edge of the disk, which is much larger than the inner edge $R_{\rm in}$. In this equation, we have used the dependence of Σ (on α, R, etc.) for a standard Shakura-Sunyaev disk.[32] A typical value of 0.01 is used for α here as it corresponds to the cold phase (low accretion state) of the disk in thermal-viscous instability theory,[30] rather than the hot phase during which α is typically assumed to be 0.1.

After the active phase, the disk enters the quiescent phase, during which matters accumulate up to the critical density so that another instability cycle follows. A very good estimate of the quiescent duration is given by[30]

$$t_{\rm quiesc} \approx 33\left(\frac{\alpha}{0.01}\right)^{-1}\left(\frac{\dot{M}}{10^{16}\ {\rm g\ s^{-1}}}\right)^{-2}\left(\frac{T_c}{3000\ {\rm K}}\right)^{-1} \times\left(\frac{M_{\rm SS}}{1.4\ M_\odot}\right)^{-1.26}\left(\frac{R_{\rm out}}{10^{10}{\rm cm}}\right)^{5.8}{\rm days}, \qquad \text{(Equation 3)}$$

where T_c is the midplane temperature and is typically taken as $\sim$3,000 K at $R_{\rm out} \approx 10^{10}$ cm. Using Equations 2 and 3, we could infer that the combination of $\alpha \approx 0.004$ and $\dot{M} \approx 3\times10^{16}$ g s^{-1} could match the temporal characteristics of FRB 180916, as shown in Figure 2.

The outer radius of the disk can be written as[33]

$$\frac{R_{\rm out}}{a} = (1.0+q)(0.5-0.227\ln q)^4 = F(q), \qquad \text{(Equation 4)}$$

where $a = (GM_{\rm SS}/4\pi^2)^{1/3}P_{\rm orb}^{2/3}$is the binary separation and $q = M_2/M_{SS}$ is the mass ratio of the system. From Equation 4 we could further obtain

$$P_{\rm orb} \approx 8F(q)^{-\frac{3}{2}}\left(\frac{R_{\rm out}}{10^{10}{\rm cm}}\right)^{\frac{3}{2}}\left(\frac{M_{\rm ss}}{1.4M_\odot}\right)^{-\frac{1}{2}}{\rm min}. \qquad \text{(Equation 5)}$$

Taking the binary parameter as $q = 0.4$ for FRB 180916, the orbital period of this system could be inferred as 40 min. Such a binary system is like some

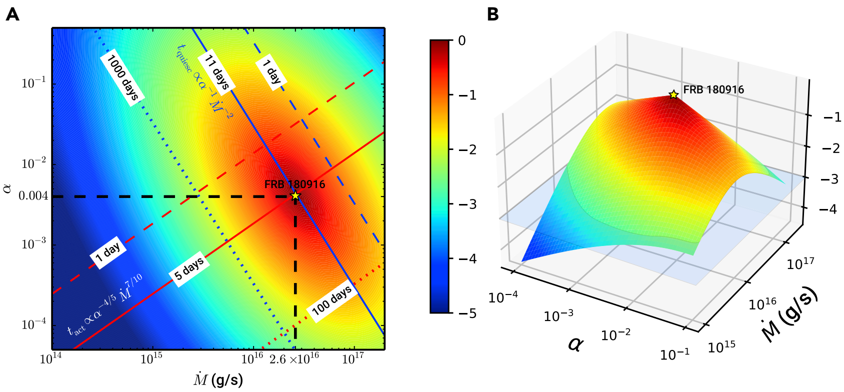


Figure 2. Constraining disk properties from temporal characteristics of periodic FRBs (A) The red lines present the $\alpha-\dot{M}$ couples for specific $t_{\rm act}$ values in a range of [1, 100] days, while the blues are the corresponding $\alpha-\dot{M}$ couples for specific $t_{\rm quiesc}$ values in a range of [1, 1,000] days. The position of the parameters inferred for FRB 180916 is marked by a star symbol. The color contours show the goodness of fit (in terms of $-\sqrt{\log^2(t_{\rm act}/5\ {\rm day})+\log^2(t_{\rm quiesc}/11\ {\rm day})}$) for FRB 180916 with different disk parameter values.
(B) A three-dimensional illustration of the color contours shown in (A).

ultracompact X-ray sources,[34,35] but the primary star here is an SS rather than an NS. Since the FRB emissions are observed along the open magnetic field lines, the binary here is preferred to be face on rather than edge on. As a result, the FRB signals would not be markedly modulated by the orbital motion since no eclipse is expected in a face-on binary system. However, orbital period modulation might still be inferred when such an FRB source is in our galaxy or a very nearby galaxy so that an X-ray or even optical counterpart could be detected.[36,37] The donor could be either a white dwarf or a low-mass star since the general trend in the stability of hydrogen-poor accretion disks is similar to that of a hydrogen disk.[35] If we assume that different-frequency emissions of FRBs are produced at different altitudes within the pulsar magnetosphere,[19] the observed chromatic activity window could be explained by the drift of the main collapse regions during the high accretion state. Such a drift is expected considering that it takes some extra waiting time for regions that have just collapsed to refill the materials to reach the critical state. Moreover, there may be a drift for the landing points of the accretion streams due to the evolution of the Alfvén radius induced by the variation of $\dot{M}_{\rm act}$ during $t_{\rm act}$.

Except for the periodic behavior, some repeating FRBs have shown sporadic/clustered behavior. These characteristics could also be naturally interpreted in our scenario. For a relatively large $P_{\rm orb}$, the accretion rate during the quiescence state is expected to become relatively small, and the quiescent duration will be increasingly long due to its dependence on $\dot{M}$ in Equation 3. On the other hand, the active window will be shortened, which could result in clustered bursts after long quiescence. In an even smaller $\dot{M}$ system, it takes a longer time to refill the crust of the SS to reach the critical point. At the same time, the smaller total disk mass to be accreted onto the crust may supply fewer radio bursts in each active window. This situation should correspond to the case of the sporadic repeating FRBs.

In our scenario, FRB 180916 is supposed to be in a binary system with a very short orbital period, which might be rare even among LMXBs. Therefore, periodic repeating FRBs may not be common in repeating FRBs. Lessons from studies on outbursts of LMXB transients indicate that mass-transfer rate variations, disk heating, irradiation, and other physical processes can produce the wealth of low-mass X-ray binary outburst light curves.[30] Long-term monitoring of a large sample of FRBs will help to reveal this temporal similarity between FRBs and LMXBs.

Conclusions

We propose that repeating FRBs may be generated from the fractional collapses of the crust of the SS. In our scenario, the FRB emission is produced along the open field lines above the polar cap of the SS after the crust matter collapse. The refilling of the accretion materials will repeat this process and hence lead to repeating FRBs. The periodic/sporadic/clustered behaviors of repeating FRBs are naturally explained by the accretion modulation in the binary system. Moreover, we could infer the basic parameters of the disk from the active/quiescent duration of the bursts.

Comparing with the NS accretion process, accretion onto an SS with a crust makes the repeating behavior feasible. An SS may form if the gravity becomes strong enough to deconfine neutron matter into strange quark matter (without going too far and collapsing to a black hole), which could happen within a star through an extremely energetic supernova (e.g., a hypernova), an accreting NS in X-ray binaries, or mergers of two NSs. The exact transition point between degenerate neutron matter and quark matter is unknown because of the lack of a clear understanding of the strong force and quark matter. We suggest that the SS in the binary here may come from the core-collapse supernova of a progenitor star with a relatively large mass in the range that is thought to give birth to an NS (8–30 $M_\odot$). The accurate ratio of SS number to NS number in the universe is unknown, so our scenario predicts that repeating FRBs may be associated with only some (not all) face-on LMXBs. The strange quark matter hypothesis dates back to the early 1970s and has neither been proved nor disproved. If our scenario is favored in the future, it could serve as indirect evidence for the existence of SS and support for the strange quark matter hypothesis. Thus we strongly encourage monitoring the face-on LMXBs for future repeating FRB searches.[38]

METHODS

Strange star with crust

At the surface of a bare SS, the quarks bound by the confinement of strong interaction have a very sharp surface with a thickness of the order of 1 fermi; i.e., the density changes abruptly from 5×10^{14} g cm^{-3} to zero on this length scale. On the contrary, the electrons bound by the coulomb force can extend several hundred fermis beyond the quark surface. As a consequence, in a thin layer several hundred fermis thick above the strange matter surface, a strong electric field is established, which is estimated to be about 10^{17} V cm^{-1} and outwardly directed. This large outward-directed electric field will support some accreted normal materials, which results in a thin crust covering the SS.[39]

Huang and Lu calculated the balance between the electrical and gravitational forces across the thin gap and found that the maximum density at the base of the crust is only one-fifth of the neutron drip point.[40] So the bottom material of the crust cannot convert into free neutrons and will not gradually flow onto the SS. As a result, when the crust gets heavier and heavier, the gap will decrease to an extent so that the crust collapse occurs. Accurate calculations show that the maximum crust mass is $M_{\rm th}\sim3.4\times10^{-6}M_\odot$ and its corresponding thickness is 10^4 cm.[40]

Accretion and crust collapse

It has been proposed that a crust may not form after the birth of an SS if the SS is rapidly rotating.[41,42] However, the formation of the crust could be guaranteed by the accretion from the companion, as in the case of our study. For a dipole magnetic field with a surface strength of $B_{\rm SS}$, the condition for magnetically funneled column accretion onto the SS is that the Alfvén radius is less than the co-rotating radius, which requires

$$B_{\rm SS}<1.0\ \times\ 10^{13}M_{\rm SS}^{\frac{5}{6}}\dot{M}_{18}^{\frac{1}{2}}R_{\rm SS,6}^{-3}P_{\rm SS,0}^{\frac{7}{6}},\qquad\text{(Equation 6)}$$

where $R_{\rm SS}$ and $P_{\rm SS}$ are the SS radius and spin period respectively. This requirement could be met even for SS magnetars if the SS is slowly rotating ($P_{\rm SS}\geq10$ s) and the accretion rate is high. Moreover, the surface magnetic field near the pole region may be dominated by a multipolar component that could be about an order of magnitude larger than the dipole field component, which has been inferred in some pulsating ultraluminous X-ray sources.[43] Therefore, the crust of the SS could be formed from materials accreted from the companion. On the other hand, when the accretion rate is low (e.g., $\sim 10^{16}$g s^{-1}), the Alfvén radius will increase and the accretion system may enter the propeller regime, which corresponds to the quiescence phase of repeating FRBs since no materials will be accreted onto the SS.

While the accreted material is thought to flow toward the polar cap region, we lack the knowledge of its geometry. Here, we assume the flow to be like elongated tongues and hit the SS in random places.[24] Taking ζ as the filling factor of the column and the number of simultaneous streams to be N, the sectional area of each stream is $\zeta A/N$, where A is the polar cap area. So materials accumulate significantly at some points of the crust surface. These regions will collapse when the local pressure at the base of the crust exceeds the critical stress. At the base of the stream, the transverse velocity of collisional diffusion in the presence of a pressure gradient (∇P) could be approximated by[25,44] $v_{\rm d} \sim 1.3\times10^{-24} T_6^{-3/2} B_{\rm SS,14}^{-2} \nabla P$ cm s^{-1} (∇P in unit of erg cm^{-4}), where T is the temperature of the surface matter, $\nabla P \sim \rho g h/r_{\rm d}$, $g = GM_{\rm SS}/R_{\rm SS}$ is the surface gravity, h is the column height, and $r_{\rm d}$ is the spreading radius of the stream. The density of each stream near the crust surface reads $\rho = \dot{M}/(\zeta A v_{\rm fd})$, where $v_{\rm fd} = (2GM_{\rm SS}/R_{\rm SS})^{1/2}/2$ is the velocity of matter that falls down. During the collapse timescale of δt, the spreading radius of the stream could be calculated as $r_{\rm d} = v_{\rm d}\delta t$. Using the closure relation of $N\pi r_{\rm d}^2 \cong \zeta A$, we obtain the expression of ζ and hence the mass of the crust that would collapse to be

$$\delta m = \frac{\pi r_{\rm d}^2}{4\pi R_{\rm SS}^2} M_{\rm th} \approx 1.0\times10^{18} N^{-\frac{1}{2}} T_6^{-\frac{3}{4}} B_{\rm SS,14}^{-1} \dot{M}_{18}^{\frac{1}{2}} h_4^{\frac{1}{2}} \delta t_{\rm 5ms}^{\frac{1}{2}} {\rm g}. \qquad \text{(Equation 7)}$$

Therefore, the amount of mass for each fractional collapse is less than 10^{18} g for $N>1$.

It should be noted that there may be several regional collapses within a short waiting time as $N>1$ and each collapse is independent in principle; i.e., the waiting time between the pulses of repeating FRBs could be only a few seconds or even shorter. However, this situation should not be frequent. If the instant collapse rate is high so that the crust of the SS loses a significant fraction of its mass in a short duration, the created tunnels would absorb materials from neighboring regions. Then to produce the next burst cluster, it will take a longer time to accrete enough mass to reach the critical state, with the equivalent isotropic crust mass being no less than $M_{\rm th}$. On average, an accretion rate of $\sim 10^{18}$ g s^{-1} is required to repeatedly produce FRBs on the timescale of seconds.

Coherent emission

Both pulsar-like mechanisms that invoke the magnetosphere of a compact object[2,45,46] and the synchrotron maser mechanism in relativistic shocks[47] could in principle (still in debate) produce coherent radio bursts. Currently, the polarization features of the repeating FRB 180301[48] and the chromatic activity window of FRB 180916 support a magnetospheric origin for the radio emission. After the crust collapse, two possible ways, i.e., the pair spraying from the tunnel and the Alfvén wave propagating in the charge-deficit region,[49] could produce pair bunching. It is difficult to clarify which mechanism works for FRBs in the real situation in this report. Here, we adopt the prior one and discuss its self-consistence. As shown in Figure 1, the polar cap region of the crust will collapse due to the continuous accretion, which results in a relativistic e^+e^- flow streaming outward along the open field lines. There are cleaner spaces in the vicinities of the tongue-like streams. Even when the accretion flow is assumed to be homogeneous in the environment above the polar cap, the ratio of the outgoing e^+e^- energy flux $F_\pm$ to the kinetic energy flux of the accretion flow $\dot{M}v_{\rm fd}^2/A$ is greater than 1 for $T_{\rm s}>1.3\times10^9$K according to Equation 1. Thus the e^+e^- flow could penetrate through the accretion flow. The parallel electric field above the crust is screened during the pair spraying. When these pairs leave the magnetosphere gap region, the gap electric field will initiate again within a short period of microseconds, which produces another following plasma cloud with a bulk Lorentz factor larger than 10^4 by pulsar-like sparking.[1] The following plasma cloud will catch up with the previous plasma cloud, and lead to the two-stream instability in the plasma, hence the coherent emission. The characteristics of the two plasma clouds are discussed below.

Consider a sparking gap with a thickness of H above the polar cap of the SS magnetosphere. The condition that curvature radiation photons produce a pair in the gap is[1]

$$\frac{3\hbar}{4\pi m_{\rm e} c R_{\rm SS}} \left(\frac{q_{\rm e}\Omega B_{\rm SS} H^2}{m_{\rm e} c^3}\right)^3 \frac{B_{\rm SS}}{B_q} \approx \frac{1}{15}, \qquad \text{(Equation 8)}$$

where $\hbar$ is the reduced Planck's constant, q_e is the electron charge, $\Omega = 2\pi/P_{\rm SS}$ is the SS angular velocity, and $B_q = m_{\rm e}^2 c^3/(q_{\rm e}\hbar)$. In the original formulation of Ruderman and Sutherland, the perpendicular component of the surface magnetic field $B_\perp$ is used rather than $B_{\rm SS}$. However, in relevant calculations and later literature, it has been widely assumed that the typical curvature radius of the magnetic field lines very near the pulsar surface is roughly $R_{\rm SS}$; i.e., higher multipole components contribute most strongly near the surface rather than the dipole field. Thus, in order to maintain the self-consistency, it is reasonable to take $B_\perp \approx B_{\rm SS}$. The gap height is then derived as

$$H \approx 100\, R_{\rm SS,6}^{\frac{1}{6}} P_{\rm SS,0}^{\frac{1}{2}} B_{\rm SS,14}^{-\frac{2}{3}}\ {\rm cm}. \qquad \text{(Equation 9)}$$

Denoting the bulk Lorentz factor of the prior plasma cloud as γ, then the overlapping radius[21,50] for the two clouds is $r_{\rm emi} \cong 2\gamma^2 H$. In a dipolar field, the curvature radius $r_{\rm c}$ is related to $r_{\rm emi}$ by $r_{\rm c} \cong 4r_{\rm emi}/(3\sin\theta_{\rm emi})$, where $\theta_{\rm emi}$ is the poloidal angle of the emission region. The corresponding characteristic frequency of curvature emission is

$$\nu_{\rm c} = \gamma^3 \frac{3c}{4\pi r_{\rm c}}. \qquad \text{(Equation 10)}$$

Therefore, the Lorentz factor of the prior plasma cloud should be

$$\gamma = 1040 \left(\frac{\nu_{\rm c}}{1.4\ {\rm GHz}}\right) \left(\frac{H}{100{\rm cm}}\right) \left(\frac{\sin\theta_{\rm emi}}{0.05}\right)^{-1}. \qquad \text{(Equation 11)}$$

This value is generally consistent with that of pairs leaving from the SS mentioned above. Equations 9 and 11 indicate that a relatively high local magnetic field of 10^{13}G is preferred in the bunching scenario to make sure that $r_{\rm emi}$ is within the light cylinder.

According to relevant calculations of the coherent emission,[21] the electron number density of the emitting region is

$$n_{\rm e} \cong 1.4\times10^{10} \left(\frac{L_{\rm FRB}}{10^{43}{\rm erg\ s^{-1}}}\right)^{\frac{1}{2}} \left(\frac{\delta t}{5{\rm ms}}\right)^{-\frac{1}{2}} \left(\frac{\nu_{\rm c}}{1.4\ {\rm GHz}}\right)^{-\frac{5}{2}} \left(\frac{H}{100{\rm cm}}\right)^{-4} \left(\frac{\sin\theta_{\rm emi}}{0.05}\right)^{2} {\rm cm}^{-3}, \qquad \text{(Equation 12)}$$

where $L_{\rm FRB}$ is the isotropic FRB luminosity, and δt is the duration of the FRB. The corresponding plasma density near the SS should be $\sim n_{\rm e}(R_{\rm SS}/r_{\rm emi})^{-3}$, which is found to be less than $n_\pm$ produced during the collapse for a reasonable range of H and $\theta_{\rm emi}$. This indicates that the crust collapse could naturally generate the required prior plasma cloud.

REFERENCES

1. Ruderman, M.A., and Sutherland, P.G. (1975). Theory of pulsars: polar gaps, sparks, and coherent microwave radiation. Astrophys. J. ***196***, 51–72.
2. Kumar, P., Lu, W., and Bhattacharya, M. (2017). Fast radio burst source properties and curvature radiation model. Mon. Not. Roy. Astron. Soc. ***468***, 2726–2739.
3. Zhang, B. (2020). The physical mechanisms of fast radio bursts. Nature ***587***, 45–53.
4. Melrose, D.B., Rafat, M.Z., and Mastrano, A. (2021). Pulsar radio emission mechanisms: a critique. Mon. Not. Roy. Astron. Soc. ***500***, 4530–4548.
5. Lorimer, D.R., Bailes, M., McLaughlin, M.A., et al. (2007). A bright millisecond radio burst of extragalactic origin. Science ***318***, 777–780.
6. Cordes, J.M., and Chatterjee, S. (2019). Fast radio bursts: an extragalactic enigma. Ann. Rev. Astron. Astrophys. ***57***, 417–465.
7. Spitler, L.G., Scholz, P., Hessels, J.W.T., et al. (2016). A repeating fast radio burst. Nature ***531***, 202–205.
8. CHIME/FRB Collaboration, Amiri, M., Andersen, B.C., Bandura, et al. (2020). Periodic activity from a fast radio burst source. Nature ***582***, 351–355.
9. Rajwade, K.M., Mickaliger, M.B., Stappers, B.W., et al. (2020). Possible periodic activity in the repeating FRB 121102. Mon. Not. Roy. Astron. Soc. ***495***, 3551–3558.
10. Dai, Z.G., Wang, J.S., Wu, X.F., and Huang, Y.F. (2016). Repeating fast radio bursts from highly magnetized pulsars traveling through asteroid belts. Astrophys. J. ***829***, 27.
11. Zhang, B. (2017). A "cosmic comb" model of fast radio bursts. Astrophys. J. Lett. ***836***, L32.
12. Gu, W.M., Yi, T., and Liu, T. (2020). A neutron star-white dwarf binary model for periodically active fast radio burst sources. Mon. Not. Roy. Astron. Soc. ***497***, 1543–1546.
13. Dai, Z.G., and Zhong, S.Q. (2020). Periodic fast radio bursts as a probe of extragalactic asteroid belts. Astrophys. J. Lett. ***895***, L1.
14. Ioka, K., and Zhang, B. (2020). A binary comb model for periodic fast radio bursts. Astrophys. J. Lett. ***893***, L26.
15. Zanazzi, J.J., and Lai, D. (2020). Periodic fast radio bursts with neutron star free precession. Astrophys. J. Lett. ***892***, L15.
16. Yang, H., and Zou, Y.C. (2020). Orbit-induced spin precession as a possible origin for periodicity in periodically repeating fast radio bursts. Astrophys. J. Lett. ***893***, L31.
17. Beniamini, P., Wadiasingh, Z., and Metzger, B.D. (2020). Periodicity in recurrent fast radio bursts and the origin of ultralong period magnetars. Mon. Not. Roy. Astron. Soc. ***496***, 3390–3401.
18. Pleunis, Z., Michilli, D., Bassa, C.G., et al. (2021). LOFAR detection of 110-188 MHz emission and frequency-dependent activity from FRB 20180916B. Astrophys. J. Lett. ***911***, L3.

19. Li, D.Z., and Zanazzi, J.J. (2021). Emission properties of periodic fast radio bursts from the motion of magnetars: testing dynamical models. Astrophys. J. Lett. ***909***, L25.
20. CHIME/FRB Collaboration, Andersen, B.C., Bandura, K.M., Bhardwaj, M., et al. (2020). A bright millisecond-duration radio burst from a galactic magnetar. Nature ***587***, 54–58.
21. Geng, J.J., Li, B., Li, L.B., et al. (2020). FRB 200428: an impact between an asteroid and a magnetar. Astrophys. J. Lett. ***898***, L55.
22. Witten, E. (1984). Cosmic separation of phases. Phys. Rev. D ***30***, 272–285.
23. Alcock, C., Farhi, E., and Olinto, A. (1986). Strange stars. Astrophys. J. ***310***, 261–272.
24. Romanova, M.M., Kulkarni, A.K., and Lovelace, R.V.E. (2008). Unstable disk accretion onto magnetized stars: first global three-dimensional magnetohydrodynamic simulations. Astrophys. J. Lett. ***673***, L171.
25. Cheng, K.S., Dai, Z.G., Wei, D.M., and Lu, T. (1998). Is GRO J1744-28 a strange star? Science ***280***, 407–409.
26. Jia, J.J., and Huang, Y.F. (2004). A numerical study of the collapse of the crust of strange stars. Chin. Astron. Astrophys. ***28***, 144–153.
27. Usov, V.V. (1998). Bare quark matter surfaces of strange stars and e^+e^- emission. Phys. Rev. Lett. ***80***, 230–233.
28. Usov, V.V. (2001). Thermal emission from bare quark matter surfaces of hot strange stars. Astrophys. J. Lett. ***550***, L179–L182.
29. Zhang, Y., Geng, J.J., and Huang, Y.F. (2018). Fast radio bursts from the collapse of strange star crusts. Astrophys. J. ***858***, 88.
30. Lasota, J.P. (2001). The disc instability model of dwarf novae and low-mass X-ray binary transients. New Astron. Rev. ***45***, 449–508.
31. Shakura, N.I., and Sunyaev, R.A. (1973). Black holes in binary systems. Observational appearance. Astron. Astrophys. ***500***, 33–51.
32. Frank, J., King, A., and Raine, D.J. (2002). Accretion Power in Astrophysics, Third Edition (Cambridge University Press).
33. Paczynski, B. (1977). A model of accretion disks in close binaries. Astrophys. J. ***216***, 822–826.
34. Juett, A.M., Psaltis, D., and Chakrabarty, D. (2001). Ultracompact X-ray binaries with neon-rich degenerate donors. Astrophys. J. Lett. ***560***, L59–L63.
35. Lasota, J.P., Dubus, G., and Kruk, K. (2008). Stability of helium accretion discs in ultracompact binaries. Astron. Astrophys. ***486***, 523–528.
36. Ge, C., Liu, R.-Y., Niu, S., et al. (2021). Revealing a peculiar supernova remnant G106.3+2.7 as a petaelectronvolt proton accelerator with X-ray observations. Innovation ***2***, 100118.
37. Samanta, T., Tian, H., Chen, B., et al. (2021). Plasma heating induced by tadpole-like downflows in the flaring solar corona. Innovation ***2***, 100083.
38. Qian, L., Yao, R., Sun, J., et al. (2020). FAST: its scientific achievements and prospects. Innovation ***1***, 100053.
39. Cheng, K.S., Dai, Z.G., and Lu, T. (1998). Strange stars and related astrophysical phenomena. Int. J. Mod. Phys. D. ***7***, 139–176.
40. Huang, Y.F., and Lu, T. (1997). Strange stars: how dense can their crust be? Astron. Astrophys. ***325***, 189–194.
41. Xu, R.X., Qiao, G.J., and Zhang, B. (1999). PSR 0943+10: a bare strange star? Astrophys. J. Lett. ***522***, L109–L112.
42. Xu, R.X., Zhang, B., and Qiao, G.J. (2001). What if pulsars are born as strange stars? Astropart. Phys. ***15***, 101–120.
43. Israel, G.L., Belfiore, A., Stella, L., et al. (2017). An accreting pulsar with extreme properties drives an ultraluminous x-ray source in NGC 5907. Science ***355***, 817–819.
44. Spitzer, L. (1965). Physics of Fully Ionized Gases (Interscience).
45. Kumar, P., and Bošnjak, Ž. (2020). FRB coherent emission from decay of Alfvén waves. Mon. Not. Roy. Astron. Soc. ***494***, 2385–2395.
46. Yang, Y.P., and Zhang, B. (2018). Bunching coherent curvature radiation in three-dimensional magnetic field geometry: application to pulsars and fast radio bursts. Astrophys. J. ***868***, 31.
47. Metzger, B.D., Margalit, B., and Sironi, L. (2019). Fast radio bursts as synchrotron maser emission from decelerating relativistic blast waves. Mon. Not. Roy. Astron. Soc. ***485***, 4091–4106.
48. Luo, R., Wang, B.J., Men, Y.P., et al. (2020). Diverse polarization angle swings from a repeating fast radio burst source. Nature ***586***, 693–696.
49. Lu, W.B., Kumar, P., and Zhang, B. (2020). A unified picture of galactic and cosmological fast radio bursts. Mon. Not. Roy. Astron. Soc. ***498***, 1397–1405.
50. Mitra, D. (2017). Nature of coherent radio emission from pulsars. J. Astrophys. Astron. ***38***, 52.

ACKNOWLEDGMENTS

The authors thank the anonymous referees for their constructive suggestions. The authors also would like to thank Xue-Feng Wu for stimulating discussions. This work is partially supported by National SKA Program of China no. 2020SKA0120300, by the National Natural Science Foundation of China (grant nos. 11903019, 11873030, 11833003, 12041306, U1938201, U1838113), by the Strategic Priority Research Program of the Chinese Academy of Sciences (multi-waveband Gravitational Wave Universe, grant no. XDB23040000), and by the science research grants from the China Manned Space Project with no. CMS-CSST-2021-B11.

AUTHOR CONTRIBUTIONS

J.G. and Y.H. led the project and wrote the manuscript. J.G. performed all the calculations, generated Figure 2, and provided the explanation for periodicity of FRBs. Y.H. suggested the basic physical origin of the FRB emission. B.L. generated Figure 1. All authors discussed the results and commented on the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

LEAD CONTACT WEBSITES

Jinjun Geng: https://orcid.org/0000-0001-9648-7295.
Yongfeng Huang: https://orcid.org/0000-0001-7199-2906.