Gravitational wave echoes from strange quark stars in the equation of state with density dependent quark masses Postprint

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Abstract

According to the recent studies, the gravitational wave (GW) echoes are expected to be generated by quark stars composed of ultrastif quark matter. The ultrastif equations of state (EOS) for quark matter were usually obtained either by a simple bag model with artifcially assigned sound velocity or by employing interacting strange quark matter (SQM) depicted by simple reparameterization and rescaling. In this study, we investigate GW echoes with EOSs for SQM in the framework of the equivparticle model with density-dependent quark masses and pairing efects. We conclude that strange quark stars (SQSs) can be sufciently compact to possess a photon sphere capable of generating GW echoes with frequencies in the range of approximately 20 kHz. However, SQSs cannot account for the observed 72 Hz signal in GW170817 event. Furthermore, we determined that quark-pairing efects play a crucial role in enabling SQSs to satisfy the necessary conditions for producing these types of echoes.

Full Text

Preamble

Gravitational wave echoes from strange quark stars in the equation of state with density-dependent quark masses

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Recent studies suggest that gravitational wave (GW) echoes may be generated by quark stars composed of ultrastiff quark matter. Ultrastiff equations of state (EOS) for quark matter have typically been obtained either through simple bag models with artificially assigned sound velocities or by employing interacting strange quark matter (SQM) described via simple reparameterization and rescaling. In this work, we investigate GW echoes using EOSs for SQM within the framework of the equivparticle model with density-dependent quark masses and pairing effects. We conclude that strange quark stars (SQSs) can be sufficiently compact to possess a photon sphere capable of generating GW echoes with frequencies in the range of approximately 20 kHz. However, SQSs cannot account for the observed 72 Hz signal in the GW170817 event. Furthermore, we determine that quark-pairing effects play a crucial role in enabling SQSs to satisfy the necessary conditions for producing these types of echoes.

Keywords: Strange quark star, Gravitational wave echoes, Color-flavour-locked phase, Strange quark matter

Introduction

The detection of gravitational waves (GWs) by the LIGO and Virgo collaborations [?, ?, ?, ?, ?] has opened significant new avenues in astrophysics for studying black holes, neutron stars, and other dense stellar objects [?, ?]. GW echoes [?, ?, ?] have been proposed as a generic feature of quantum corrections at the horizon scale in post-merger GW signals from binary coalescence events, particularly those involving black holes. In general, the emission of GW echoes requires dense stellar objects featuring a photon sphere located at $R_p = 3M$, where M denotes the mass of the dense object [?, ?, ?, ?]. The photon sphere can partially trap GWs, thereby producing echoes.

This type of photon sphere can be found in both black holes [?] and superdense stars [?, ?], whose radii must be smaller than R_p. For black holes, besides the photon sphere, GW echoes necessitate a secondary reflecting surface to circumvent GW absorption, which may be related to quantum effects in proximity to the black hole horizon [?]. The possible occurrence of GW echoes at a frequency of approximately 72 Hz, with a statistical significance level of 4.2σ, was first investigated in Ref. [?] for the GW170817 event, where the echoes were interpreted as resulting from quantum effects near the black hole horizon. However, Ref. [?] indicated that GW echoes can be generated not only by quantum corrections at the horizon scale but also by exotic super-compact objects [?, ?]. Moreover, a simplified incompressible equation of state was utilized, revealing that a highly compact stellar object with radius close to Buchdahl's radius [?] $R_B = 9/4M$ is required to produce GW echoes at such low frequencies. Specifically, Buchdahl's radius represents the minimum radius for compact stars [?]. Additionally, for compact stars to produce GW echoes, their radii must fall within the range $R_B < R < R_P$. This compactness criterion essentially precludes realistic equations of state for neutron stars [?]. Consequently, researchers are exploring alternative compact stellar objects, such as strange quark stars (SQSs) [?], which consist of strange quark matter (SQM) [?, ?, ?, ?].

In Ref. [?], the authors examined whether a more realistic EOS for quark stars can emit GW echoes. They employed the confined-isospin-density-dependent-mass model with additional scalar and vector Coulomb terms of SQM [?] and confirmed that SQSs with realistic EOS cannot be categorized as ultra-compact objects featuring a photon sphere to generate GW echoes. Moreover, in Ref. [?], the authors utilized an interacting quark matter EOS unifying interacting phases via simple reparameterization and rescaling. They found that GW echoes are possible for quark stars with large central pressure. Furthermore, GW echoes were examined in $f(R,T)$ gravity metric formalism within the MIT bag model and the color-flavor-locked (CFL) EOSs. The authors indicated that, under certain considerations, realistic interacting quark matter can lead to stellar structures sufficiently compact to feature a photon sphere outside the stellar boundary, and thereby can echo GWs [?, ?]. Additionally, the author investigated GW echoes from SQSs for various EOSs, including the MIT bag model and linear and polytropic EOSs. However, only the MIT bag model and linear polytropic EOSs were found to emit GW echoes at a frequency range of approximately tens of kilohertz [?].

In a recent study [?], GW echoes produced by strangeon stars composed of strange-cluster matter in the solid state were investigated. The authors recast the EOS of strange-cluster matter into dimensionless forms via reparameterization and rescaling. Furthermore, they concluded that strangeon stars are typically compact enough to have a photon sphere. This sphere reflects GWs that fall within the gravitational potential barrier, producing GW echoes with a minimum echo frequency of approximately 8 kHz, extending even to frequencies as low as $\mathcal{O}(100)$ Hertz.

Nonetheless, in the aforementioned studies, investigations concerning GW echoes have primarily concentrated on either a basic MIT bag model or parameterized EOSs for SQM. In this study, we employ EOSs for SQM based on the equivparticle model with density-dependent quark masses. Within this model, quark masses are scaled according to the baryon number density, replicating the complex interactions among quarks [?]. This model was initially developed as a quark mass-density-dependent model [?, ?, ?, ?] and later renamed as the equivparticle model after explicitly introducing the concept of effective quark chemical potential [?]. Given its clear physical picture and accurate thermodynamic treatments, the model has been widely utilized in studying quark matter properties and quark star structures [?, ?, ?, ?, ?]. In Ref. [?], we investigated the symmetry energy of SQM and tidal deformability of SQSs within this model. Our findings indicate that the region of absolute stability for SQM can be significantly widened with sufficiently large isospin symmetric parameter, yielding results that simultaneously satisfy constraints imposed by astrophysical observations of PSR J1614-2230, with $1.928 \pm 0.017 M_\odot$ [?] and tidal deformability $70 \leq \Lambda_{1.4} \leq 580$ measured in the GW170817 event [?]. Upon application of the EOSs in this model, we determine that SQSs can produce GW echoes with frequencies in the order of kilohertz, which is consistent with previous findings, provided that they are composed of SQM in the CFL phase [?, ?].

The paper is organized as follows: Section II provides a brief overview of the EOSs for SQM in the CFL phase within the equivparticle model. Section III presents the process of calculating the GW echoes and scrutinizes the corresponding numerical results. Finally, a concise summary is presented in Section IV.

II. EOS of CFL Quark Matter in Equivparticle Model

The thermodynamic potential density for CFL SQM can be expressed as:

$$\Omega_{\mathrm{CFL}} = -\sum_{i=u,d,s} \frac{g_i}{2\pi^2} \int_0^\nu p^2 \sqrt{p^2 + m_i^2}\, dp - \frac{3\Delta^2 \bar{\mu}^2}{\pi^2} + B,$$

where $g_i = 2 \times 3 = 6$ corresponds to the degeneracy factor, ν denotes the common Fermi momentum, $\bar{\mu} \equiv (\mu_u + \mu_d + \mu_s)/3$ is the averaged chemical potential of quarks, Δ denotes the quark pair energy gap, B denotes the bag constant (which we take as $B^{1/4} = 180$ MeV in the following calculations), and m_i denotes the density-dependent quark mass which can be scaled as:

$$m_i = m_{i0} + m_I = m_{i0} + \frac{D}{n_b^{1/3}},$$

where $m_{u0} = m_{d0} = 5$ MeV and $m_{s0} = 100$ MeV are the quark current masses [?], m_I denotes the interacting part and is the same for all flavors, and D denotes a model parameter representing the strength of confinement. Due to the lack of an accurate value for Δ, in this model Δ is considered a free parameter. It should be emphasized that the quark chemical potential μ_i is effective. Furthermore, the real chemical potential $\mu_{i,\mathrm{real}}$ can be related to the effective one due to the density-dependent quark mass [?]. To ensure maximum pairing, the common Fermi momentum ν can be obtained by taking the derivative of Ω_{CFL} with respect to ν, i.e., $\partial\Omega_{\mathrm{CFL}}/\partial\nu = 0$, yielding:

$$\sum_i \sqrt{\nu^2 + m_i^2} = 3\bar{\mu}.$$

The integration in Eq. (1) can be conducted as follows:

$$\Omega_{\mathrm{CFL}} = -\sum_i \frac{g_i}{24\pi^2}\left[8\mu_i\nu^3 - 3(2\nu^2 + m_i^2)\sqrt{\nu^2 + m_i^2}\right] - \frac{3\Delta^2\bar{\mu}^2}{\pi^2} + B,$$

from which one can readily obtain the quark number density for each quark flavor according to the relation $n_i = -\partial\Omega_{\mathrm{CFL}}/\partial\mu_i$, i.e.:

$$n_b = n_u = n_d = n_s = \frac{\nu^3 + 2\Delta^2\bar{\mu}}{\pi^2},$$

where $n_b \equiv (n_u + n_d + n_s)/3$ denotes the baryon number density.

The energy density is:

$$E = \Omega_{\mathrm{CFL}} + \sum_i \mu_i n_i = \Omega_{\mathrm{CFL}} + 3n_b\bar{\mu}.$$

Due to the density-dependent quark mass, the pressure of the system is:

$$P = -\Omega_{\mathrm{CFL}} + n_b \sum_i \frac{\partial\Omega_{\mathrm{CFL}}}{\partial m_i}\frac{\partial m_i}{\partial n_b},$$

where the second term on the right side is crucial to guarantee thermodynamic consistency. The derivatives are respectively:

$$\frac{\partial\Omega_{\mathrm{CFL}}}{\partial m_i} = \frac{g_i m_i}{8\pi^2}\left[\nu\sqrt{\nu^2 + m_i^2} - m_i^2 \ln\left(\frac{\nu + \sqrt{m_i^2 + \nu^2}}{m_i}\right)\right],$$

$$\frac{\partial m_i}{\partial n_b} = -\frac{1}{3}Dn_b^{-4/3}.$$

III. GW Echo Frequency of CFL SQS in Equivparticle Model

To generate GW echoes, the EOSs of SQM must be sufficiently stiff to feature a photon sphere at $R_P = 3GM$. To examine how the stiffness of the EOS changes with model parameters D and Δ, we express the velocity of sound as a function of D (upper panel) and Δ (lower panel) for different baryon number densities, as shown in Fig. 1 [Figure 1: see original paper]. Based on the upper panel of Fig. 1, at a fixed $\Delta = 150$ MeV, the sound velocity decreases as D increases, indicating a softening of the EOS with larger D. Conversely, with fixed $D = 100$ MeV, the sound velocity increases with Δ, implying that the EOS becomes stiffer for large Δ. Therefore, based on Fig. 1, the EOS can be inferred to become stiffer by simultaneously reducing D and increasing Δ. Hence, a stiff EOS can be realized by setting $D = 0$ and simultaneously adopting a large Δ. However, the value of Δ cannot be arbitrarily chosen for a given D and is dependent on the density of SQM. To investigate this point, the following steps should be considered.

First, by combining Eqs. (3) and (5) and then eliminating the averaged quark chemical potential $\bar{\mu}$, we obtain $\sum_i \sqrt{\nu^2 + m_i^2} = 2\Delta^2(\pi^2 n_b - \nu^3)$. Based on this, a function of ν can be introduced:

$$\Phi(\nu) = 2\Delta^2(\pi^2 n_b - \nu^3) - \sum_i \sqrt{\nu^2 + m_i^2}, \quad (\nu \geq 0).$$

Here, note that the purpose of introducing the function $\Phi(\nu)$ is only to determine the relation between model parameters D and Δ. Additionally, ν should be considered as a variable of the function $\Phi(\nu)$, although it has the meaning of Fermi momentum.

The derivative of $\Phi(\nu)$ with respect to ν can be easily obtained:

$$\frac{d\Phi(\nu)}{d\nu} = -6\Delta^2\nu^2 - \sum_i \frac{\nu}{\sqrt{\nu^2 + m_i^2}},$$

where $d\Phi(\nu)$ is observed to be consistently negative (equal to zero only when $\nu = 0$). This suggests that $\Phi(\nu)$ increases with decreasing ν, thereby indicating the existence of a maximum value of $\Phi(\nu)$ at $\nu = 0$, namely:

$$\Phi_{\max}(\nu = 0) = 3\pi^2 n_b 2\Delta^2 - \sum_i m_i.$$

For Eq. (12), we should indicate that $\nu = 0$ is only a limiting case, and its purpose is to provide the D-Δ window. Additionally, in the following calculations, non-physical values of ν, such as $\nu = 0$, will not be considered.

If Eq. (10) admits a solution for ν, then it implies that the maximum value $\Phi_{\max}(\nu = 0)$ should be no less than 0. This in turn yields the inequality:

$$\Delta \leq \sqrt{\frac{\sum_i m_i(n_b, D)}{6\pi^2 n_b}},$$

where the quark mass m_i is explicitly expressed as a function of baryon number density n_b and model parameter D.

Evidently, by assigning a value to the model parameter D, the maximum value of Δ can be expressed as a function of baryon number density. Furthermore, the maximum value of Δ increases with n_b for a fixed D. This implies that the highest attainable value of Δ is contingent upon the potential minimal value of the density of SQM for a specific D. Considering that the saturation density of normal nuclear matter is $n_0 \approx 0.16\ \mathrm{fm}^{-3}$, we assume that the density of SQM is not smaller than n_0, and the minimum baryon number density of SQM is designated to be $n_{b,\min}$. To establish a range of values for Δ, we set $n_{b,\min} = n_0, 2n_0$, and $3n_0$ in Eq. (13).

In Fig. 2 [Figure 2: see original paper], we present the model parameter window in the Δ-$D^{1/2}$ diagram for different minimum baryon number densities $n_{b,\min}$ of SQM. For instance, if the model parameters lie within the region below the solid black line, a solvable EOS for SQM with a minimum density of $n_{b,\min} = n_0$ can be obtained. The black dashed and dotted lines serve the same purpose but correspond to minimum densities of $2n_0$ and $3n_0$, respectively. Referring to previous studies on CFL SQM within this model [?], when assigning a value of $\Delta = 100$ MeV, we find that a solvable EOS spans a broad range of $D^{1/2}$, from 0 to beyond 130 MeV. Notably, as D rises, the maximum value of Δ decreases for a specified $n_{b,\min}$. Additionally, increasing $n_{b,\min}$ significantly expands the parameter window.

For subsequent calculations, we select three representative model parameter sets: $(D/\mathrm{MeV}, \Delta/\mathrm{MeV}) = (70, 100)$, $(70, 359.1)$, and $(70, 500)$, denoted as sets A, B, and C, respectively, marked by solid squares in Fig. 2.

Before delving into the mass-radius relation for SQSs, we should first check whether the condition $\Delta > m^2/4\bar{\mu}$ can be fulfilled. This guarantees that the CFL SQM can stably exist [?]. In Fig. 3 [Figure 3: see original paper], we show the difference between Δ and $m^2/4\bar{\mu}$ versus baryon number density ranging from n_0 to $10n_0$ for the typical model parameters chosen in Fig. 2. Based on this figure, the difference between Δ and $m^2/4\bar{\mu}$ is positive, which implies that the condition $\Delta > m^2/4\bar{\mu}$ is fulfilled. Additionally, with increasing baryon number density, the difference becomes significant. Furthermore, large Δ provides a large difference between Δ and $m^2/4\bar{\mu}$.

To explore whether SQSs in the current model can possess a photon sphere and subsequently produce GW echoes, one should first calculate the EOSs for CFL SQM. Following this, the mass-radius relation for hydrostatically equilibrated SQSs can be determined by solving the Tolman-Oppenheimer-Volkoff (TOV) equations:

$$\frac{dP}{dr} = -\frac{G(E+P)(m+4\pi r^3 P)}{r(r-2Gm)},$$

$$\frac{dm}{dr} = 4\pi r^2 E,$$

where E and P denote the energy density and pressure at radius r, $G = 6.707 \times 10^{-45}$ MeV^{-2} is the gravitational constant, and $m(r)$ denotes the gravitational mass within radius r.

The resulting mass-radius relations are illustrated in Fig. 4 [Figure 4: see original paper]. Based on this figure, when $\Delta = 100$ MeV, the maximum mass for case A is determined to be below the photon sphere line. This implies that no GW echoes can be generated in this case. When $\Delta = 359.1$ MeV, the maximum mass of the SQS nicely locates at the photon sphere line, signifying the critical state for the SQS to possess a photon sphere. For a larger value of $\Delta = 500$ MeV, the EOS corresponding to the maximum mass of SQSs surpasses the photon sphere line, indicating its capability to produce GW echoes. This suggests that the configurations for SQSs, ranging from point 1 to point 2 in the detailed review profile shown in Fig. 4, exhibit the potential to generate GW echoes. Thus, for a fixed $D = 70$ MeV in this instance, the value of the maximum mass of SQS, represented by solid dots in Fig. 4, increases with Δ. This correlation is further emphasized in Fig. 1, where the velocity of sound rises concomitantly with Δ. Moreover, for a constant D, a specific Δ value can be determined that positions the maximum mass of the SQS exactly on the photon sphere line.

In Fig. 2, the red line illustrates the correlation between Δ and $D^{1/2}$ that leads to the most massive SQSs located precisely on the photon sphere line. Furthermore, with an error at the level of 0.1%, it can be fitted as:

$$\Delta = \Delta_{\text{min}} + \left(c_1\sqrt{D/\text{MeV}} + c_2\right)\exp\left(-\frac{D/\text{MeV}}{c_3}\right),$$

where the coefficients are $c_1 \approx 114.5837$, $c_2 \approx 85.3983$, and $c_3 \approx 52.5021$. Based on this equation, the parameter Δ increases with D and $\Delta_{\text{min}} \approx 355.6398$ MeV is the minimum value of Δ at $D = 0$. This means that SQM in the CFL state within the current model can satisfy the requirement of featuring a photon sphere for SQSs. Consequently, the parameter sets (D, Δ) that qualify SQSs to produce GW echoes should lie above the red line illustrated in Fig. 2. Hence, only parameter set C aligns with the SQS configurations requisite for generating GW echoes. Additionally, from Eqs. (13) and (16), we deduce that the least density necessary for SQM to feature a photon sphere within this model is around $n_{b,\text{min}} \approx 0.1223$ fm^{-3}.

To derive the frequency of GW echoes, the time taken for light to traverse from the center of the star to its photon sphere [?] should be computed:

$$\tau_{\text{echo}} = \int_0^{3GM} \frac{e^{\Phi(r)}}{\sqrt{1-2Gm(r)/r}}\, dr.$$

When $0 < r < R$, $m(r) = 4\pi \int_0^r E(r')r'^2 dr'$. The gravitational potential $\Phi(r)$ can be derived by integrating the differential equation:

$$\frac{d\Phi(r)}{dr} = -\frac{1}{E+P}\frac{dP}{dr},$$

which can be solved together with the TOV equations in Eqs. (14) and (15). When $R < r < 3GM$, $m(r) = M$, $e^{2\Phi} = 1 - 2M/r$, and $P = \rho = 0$. Here, P and E denote the pressure and energy density, respectively, as determined by the EOS. Finally, the GW echo frequency can be evaluated by $\omega_{\text{echo}} = \pi/\tau_{\text{echo}}$.

In Fig. 5 [Figure 5: see original paper], we present the GW echo frequency ω_{echo} and the mass of SQS versus central pressure P_0 for case C from point 1 to point 2 in the detailed review profile in Fig. 4. Evidently, as shown in Fig. 5, the mass of SQS increases with central pressure, while the GW echo frequency decreases. This can be interpreted as follows: with higher pressure, the SQS will have a larger mass. Based on $R_p = 3GM$, the photon sphere will be situated further from the center of the SQS. This will result in light requiring more time to travel from the center of the SQS to the photon sphere, thereby leading to a smaller ω_{echo}. Therefore, given the appropriate model parameters, the most massive SQS exhibits the lowest GW echo frequency.

In Fig. 6 [Figure 6: see original paper], we show the GW echo frequencies for the most massive SQSs within the model parameter window where Δ and D are in the ranges of 400-800 MeV and 0-130 MeV, respectively. According to Fig. 2, the selected model parameter ranges ensure that the most massive SQSs are positioned above the photon sphere line, thereby capacitating them to generate GW echoes. Notably, with a constant Δ, a negligible shift is observed in the GW echo frequency as D escalates. Conversely, with a stable D, the GW echo frequency undergoes notable variation with changes in Δ; specifically, it transitions from approximately 22.8 kHz at $\Delta = 400$ MeV to approximately 18.8 kHz at $\Delta = 800$ MeV. In conclusion, the GW echo frequencies predominantly oscillate around 20 kHz in this model, which aligns with the GW frequency magnitudes reported in prior studies [**?**, **?**, **?**]. Additionally, the unmarked region designated as “imbalanced SQM” in the figure signifies scenarios where both Δ and D are substantially elevated, causing the CFL SQM to be unable to maintain pressure equilibrium. This leads to the unstable existence of the SQS.

IV. Summary

In this study, we investigated the GW echoes generated by SQSs within the framework of an equivparticle model. Distinct from prior research that relied on the basic MIT bag model with predetermined sound velocities, our approach utilized EOSs for SQM in the equivparticle model enriched with density-dependent quark masses. This integration encapsulates both confinement and quark pairing effects. Significantly, our findings emphasize the crucial role of quark pairing effects in enabling a photon sphere and thereby facilitating the production of GW echoes. As the value of Δ increases, the EOS for SQM becomes stiffer, allowing the mass-radius relation of SQSs to intersect with the photon sphere line and therefore yield GW echoes. Additionally, for specific model parameters Δ and D, the SQS bearing the maximum mass showcases the lowest GW echo frequency. We also estimated the GW echo frequencies for the most massive SQSs within the chosen model parameters. Conclusively, while D imparts minimal influence on the GW echo frequency, an increment in Δ results in significant alterations. The predominant GW echo frequencies hover around 20 kHz, which contrasts with the observed 72 Hz signal in the GW170817 event. This underscores that SQSs, as conceptualized in our current model, should not be construed as ultra-compact objects radiating such low-frequency GW echoes. Future research may need to consider additional effects or avenues [**?**, **?**, **?**].

Author Contributions
All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Jian-Feng Xu, Lei Cui, Zhen-Yan Lu, Cheng-Jun Xia and Guang-Xiong Peng. The first draft of the manuscript was written by Jian-Feng Xu and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability Statement
The data that support the findings in this study are openly available at https://www.doi.org/10.57760/sciencedb.12532 and https://cstr.cn/31253.11.sciencedb.12532.

Conflict of Interest
The authors declare that they have no competing interests.

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