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Oscillations of hypothetical strange stars as an efficient source ultra-high-energy particles

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We investigate the dynamical behavior of strange quark matter (SQM) objects, such as stars and planets, when subjected to radial oscillations induced by tidal interactions in stellar systems. Our study demonstrates that SQM objects can efficiently convert mechanical energy into hadronic energy due to the critical mass density at their surfaces of $4.7\times10^{14}\,\mathrm{g\,cm^{-3}}$, below which SQM becomes unstable and decays into photons, hadrons, and leptons. We show that even small-amplitude radial oscillations, with a radius change of as little as 0.1%, can result in significant excitation energies near the surface of SQM stars. This excitation energy is rapidly converted into electromagnetic energy over short timescales (approximately 1 ms), potentially leading to observable astrophysical phenomena. Higher amplitude oscillations may cause fragmentation or dissolution of SQM stars, which has important implications for the evolution of binary systems containing SQM objects and the emission of gravitational waves.

Keywords: SQM, strange quark stars, tidal interactions, radial oscillations, energy conversion

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1. Introduction

Strange quark matter (SQM) has been hypothesized to be the true ground state of baryonic matter since the seminal work by Witten [1]. Neutron stars composed of SQM were studied soon after [2]. Under extreme conditions of pressure and density, matter containing up, down, and strange quarks can be more stable than ordinary nuclear matter.

Recent observations have renewed interest in possible SQM objects, especially of planetary mass. SQM could exist at any mass down to planetary values [3], and even in smaller "strange nuggets" [4]. Pulsar systems such as PSR B1257+12 show planets with unusually high densities [5, 6], hinting these objects may be SQM.

In stellar or planetary systems, tidal interactions are common, inducing oscillations in compact objects. Predicting the signatures and stability of such oscillations in SQM matter is essential for astrophysical modeling. Previous work explored SQM stars and their gravitational-wave properties [7], but the specific role of small radial oscillations remains less investigated.

Guided by these considerations, we study the behavior of SQM stars and planets undergoing radial oscillations [8]. Our main goal is to see how mechanical energy near the surface translates into hadronic and electromagnetic energy, given that SQM becomes unstable below a critical density $\rho_0 \sim 4.7 \times 10^{14}\,\mathrm{g\,cm^{-3}}$. Even a small ($\sim 0.1\%$) change in radius can push the surface layer below this threshold density, triggering rapid energy release. Such processes could have observable effects, especially in binary systems or gravitational wave sources.

2. Objectives and Key Concepts

Main Objectives

- Investigate the dynamical behavior and stability of SQM stars or planets subjected to radial oscillations due to tidal forces.
- Understand how mechanical (oscillatory) energy is converted into hadronic and electromagnetic energy, focusing on surface instabilities.
- Assess astrophysical consequences, including fragmentation of SQM objects, the potential for gravitational wave emission, and other observational effects.

Strange Quark Matter (SQM)

SQM is a hypothetical form of matter with up, down, and strange quarks in roughly equal proportions. Under the MIT bag model [1], SQM can be more stable than nuclear matter at high densities, possibly forming large or small (nugget) objects.

Saturation Density ρ_0

Below a critical density ρ_0, SQM decays into photons, hadrons, and leptons. In our model,

$$\rho_0 = 4.665 \times 10^{14}\,\mathrm{g\,cm^{-3}}.$$

For densities above ρ_0, quark interactions stabilize SQM in the MIT bag model.

Radial Oscillations

Monopole or breathing-mode oscillations are uniform expansions/contractions of a star or planet. Even minor radial changes can alter the near-surface density and stability [8].

3. Methodology

We examine SQM star or planet evolution under tidal interactions in binary systems, incorporating excitation and energy conversion processes into stellar dynamics. Our approach includes:

- Modeling radial oscillations and their damping via electromagnetic energy release.
- Analyzing maximum oscillation amplitudes for which SQM objects remain intact.

Numerical Simulations

We solved Tolman-Oppenheimer-Volkoff (TOV) equations with equations of state for SQM. Radial oscillations were induced by perturbing equilibrium configurations and following changes in density/pressure. The resulting excitation energy and potential for fragmentation were evaluated.

Stability Analysis

We sought the maximum oscillation amplitude before fragmentation or dissolution. Tidal forcing inputs energy; electromagnetic release drains it. If release is fast enough, SQM may remain stable unless amplitudes grow too large.

MIT Bag Model Details

We adopt the MIT bag model [1, 9], in which:

$$\rho c^2 = \varepsilon_q + B,$$

with B the bag constant and ε_q the fermion energy density. Electrons and a finite s-quark mass also enter the equation of state [10]. We set $B = 60\,\mathrm{MeV\,fm^{-3}}$, $m_s = 150\,\mathrm{MeV}$. Under these choices, SQM is stable at zero pressure.

4. Results

Using chemical equilibrium and charge neutrality in the bag model, we derive the energy per baryon ε/n as a function of baryon density n. Figure 1 shows the minimum at saturation density n_0, where SQM is most stable.

Excitation Energy per Baryon

Let $\epsilon_{\rm exc}$ be the energy above the minimum from density fluctuations near n_0. Expanding around n_0,

$$\epsilon_{\rm exc} = \frac{1}{2}\left.\frac{d^2\epsilon}{dn^2}\right|_{n_0}(\Delta n)^2,$$

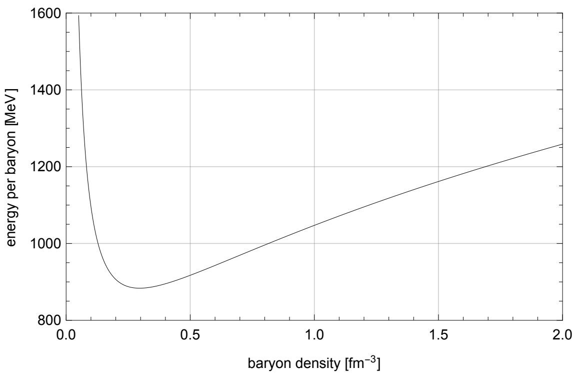

Figure 1: Energy per baryon vs. baryon density for SQM in the MIT bag model with $B = 60\,\mathrm{MeV\,fm^{-3}}$, $m_s = 150\,\mathrm{MeV}$. The minimum at n_0 identifies the saturation density.

where $\Delta n = n(x) - n_0$. The convexity parameter β_s is

$$\beta_s = \frac{n_0^2}{\epsilon_{\min}} \left.\frac{d^2\epsilon}{dn^2}\right|_{n_0}, \quad \epsilon_{\min} = \epsilon(n_0).$$

A radial fraction $x = \Delta R/R$ measures the amplitude of monopole oscillations. Integrating $\epsilon_{\mathrm{exc}}(r)$ over volume gives the total excitation E_{exc}.

Scaling Laws for Energy in Monopole Perturbations

At the saturation point $n_s = 0.296136\,\mathrm{fm^{-3}}$, $\epsilon_s = 883.623\,\mathrm{MeV}$, $\beta_s = 0.307124$. The excess $\Delta\epsilon$ from small density changes Δn around n_s reads $\Delta\epsilon = \frac{1}{2}\,\epsilon''(n_s)(\Delta n)^2$.

Small-mass SQM objects (nearly constant density). When $n(r) \approx n_s$, and $r \to r(1+x)$ for $x \ll 1$, the density changes by $\Delta n = 3n_s x$. Then

$$\Delta\epsilon = \tfrac{9}{2}\,\beta_s\,\epsilon_s\,x^2 \approx 1221.22\,x^2\,\mathrm{MeV}.$$

Multiplying by baryon number $N_B = Mc^2/\epsilon_s \approx 3.794 \times 10^{51}\ (M/M_\oplus)$ yields the total energy to radiate:

$$E_{\mathrm{T}} = \tfrac{9}{2}\,\beta_s\,Mc^2\,x^2 \approx 7.416 \times 10^{48}\,\mathrm{erg}\,\tfrac{M}{M_\oplus}\,x^2. \tag{1}$$

This scales as x^2. E.g., for an Earth-mass SQM planet with $x = 10^{-5}$, $E_{\mathrm{T}} = 7.4 \times 10^{38}$ erg.

Higher-mass SQM stars. Keeping x fixed, only a thin subsaturation zone near the surface contributes to the excitation. By expanding solutions to Einstein's equations, we find to leading order:

$$E_{\mathrm{T}} = 18\pi\,\beta_s^2\,\epsilon_s\,n_s\,\frac{c^2 R^4}{GM}\,H_\Phi\,x^3, \qquad \frac{\delta R_x}{R} \equiv \frac{3\beta_s}{\Phi}\left(1 - \frac{7}{3}\Phi\right)x \ll 1, \tag{2}$$

where $\Phi = GM/(Rc^2)$ and H_Φ is a relativistic correction. This scales as x^3. For a $1.4\,M_\odot$ star at $R = 10.31\,\mathrm{km}$, $E_{\mathrm{T}} \approx 6.634 \times 10^{54}\,x^3$ erg.

Analysis of Radial Oscillations

Small perturbations around equilibrium reveal that expanding the star lowers near-surface densities below n_0, exciting SQM to higher-energy states. Figure 2 shows the mass-radius curve for SQM and the energy release E_{T} from a thin surface zone if x is nonzero.

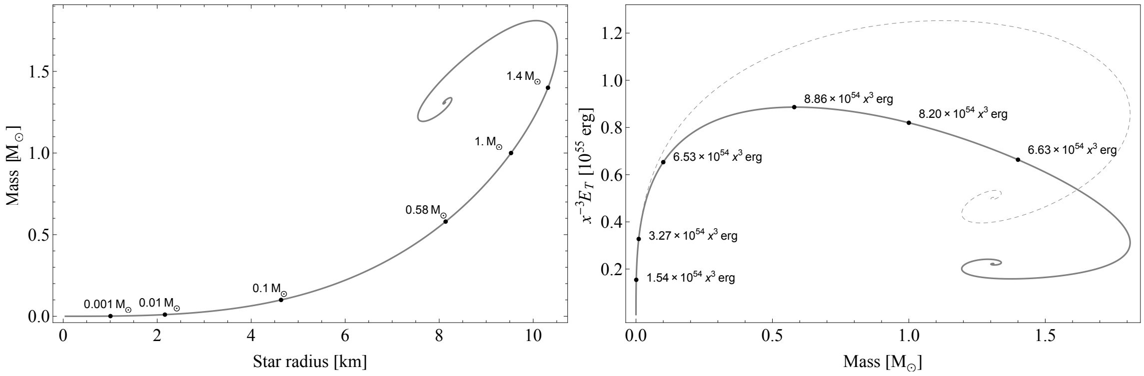

Figure 2: *Left:* Mass-radius relation for SQM ($B = 60\,\mathrm{MeV\,fm^{-3}}$, $m_s = 150\,\mathrm{MeV}$). *Right:* Energy (2) released by a monopole oscillation of amplitude x, ignoring or including a relativistic factor H_Φ.

Conversion to Electromagnetic Energy

Below saturation density, SQM rapidly decays into photons, hadrons, leptons. We estimate the electromagnetic release rate $P = E_{\mathrm{exc}}/\tau$, with τ a few oscillation periods. Even $x = 0.001$ yields $\sim 1\,\mathrm{keV}$ per baryon near the surface, quickly emitted on a timescale of $\sim 1\,\mathrm{ms}$.

Rapid Energy Release

High amplitudes can produce multi-MeV per baryon, totaling $\sim 10^{51}\,\mathrm{erg}$ at rates up to $10^{55}\,\mathrm{erg\,s^{-1}}$. Such violent events could fragment or dissolve the star altogether.

Baryon Density and Energy per Baryon in Excited SQM

Figure 3 illustrates how a $1.4\,M_\odot$ star's surface region becomes unstable at 10% expansion. The dashed line indicates n_0 saturation. The region $n < n_0$ gains ϵ_{exc} and rapidly radiates away.

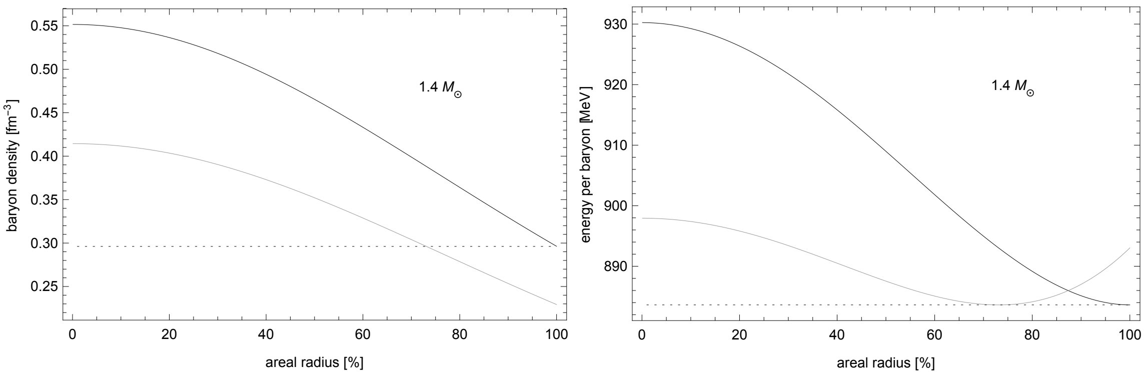

Figure 3: Baryon density (left) and energy per baryon (right) for a $1.4\,M_\odot$ SQM star in equilibrium (black) vs. a 10% radial expansion (gray). Dashed lines show n_0 and its corresponding energy.

Total Energy to Be Radiated

For constant-density (planetary) SQM, (1) implies $E_{\mathrm{T}} \propto x^2$. For larger SQM stars, (2) yields $E_{\mathrm{T}} \propto x^3$. Table 1 summarizes energies, radii, and baryon numbers for sample objects, showing that even $x = 0.001$ can release sizable energy.

Mass	N_B	R	x	$E_{\rm T}$	r_c	$N_B(r>r_c)$	$\bar{\epsilon}_{\rm exc}$ ($\epsilon_{\rm exc}\|_R$)
1.0 $M_\oplus$	3.790×10^{51}	145.1 m	0.001	7.315×10^{42} erg	0.0 m	3.790×10^{51}	1.205(1.221) keV
1.4 $M_\odot$	2.032×10^{57}	10.31 km	0.001	6.630×10^{45} erg	10.29 km	1.288×10^{55}	321.3(961.1) eV
			0.01	6.592×10^{48} erg	10.06 km	1.278×10^{56}	32.19(96.14) keV
			0.1	6.160×10^{51} erg	7.535 km	1.158×10^{57}	3.321(9.450) MeV

Table 1: Sample SQM objects at different radial amplitudes. N_B = total baryon number, R = (areal) radius, x = fractional amplitude, $E_{\rm T}$ = eventual radiated energy, r_c = conversion radius above which $n < n_0$, $\bar{\epsilon}_{\rm exc}$ = average excitation per baryon, $\epsilon_{\rm exc}|_R$ = excitation at the surface.

5. Discussion and Astrophysical Implications

Sensitivity to Oscillations. Our results highlight how SQM surfaces respond acutely to radial oscillations. Even $x \sim 0.1\%$ triggers noticeable energy release near n_0, quickly radiated as electromagnetic energy on $\sim$ 1 ms timescales. Larger x can unbind outer layers, fragmenting or dissolving the star.

Implications for Gravitational Waves. Energy lost to electromagnetic radiation changes the dynamics in SQM binaries. Such systems might produce distinct gravitational wave signatures if partial dissolution occurs. Accounting for this effect in wave templates could refine interpretation of signals involving SQM objects.

Observational Prospects. The short, intense photon bursts or transients could coincide with SQM star oscillations or mergers. If fragmentation forms smaller SQM bodies, these might persist as strange nuggets or be ejected.

6. Conclusion and Future Work

Energy Conversion and Stability: Even small radial amplitudes ($x \lesssim 0.001$) can lead to $\sim$ 1 keV per baryon above the surface, released in milliseconds. Larger amplitudes ($x \gtrsim 0.01$) may exceed outer-layer binding energies, causing fragmentation or dissolution.
Gravitational Wave Sources: Damping by electromagnetic energy release can alter orbital evolution and waveforms in binary systems containing SQM. More precise modeling could improve gravitational-wave detection and parameter extraction from such sources.
Astrophysical Impact: Oscillation-induced instabilities or fragmentation can shape the fate of SQM stars, produce exotic transients, and generate smaller SQM lumps. Observing these phenomena would bolster the case for SQM's existence.
Future Work:

- Investigate detailed radiation mechanisms and multiwavelength signatures of decaying SQM surfaces.
- Explore long-term evolution and repeated oscillation cycles in binary or cluster environments.
- Incorporate SQM oscillation effects into gravitational-wave templates to test observational data for possible SQM signals.

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