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Internal x-ray plateau in short GRBs: Signature of supramassive fast-rotating quark stars?

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A supramassive, strongly magnetized millisecond neutron star (NS) has been proposed to be the candidate central engine of at least some short gamma-ray bursts (SGRBs), based on the “internal plateau” commonly observed in the early x-ray afterglow. While a previous analysis shows a qualitative consistency between this suggestion and the Swift SGRB data, the distribution of observed break time t_b is much narrower than the distribution of the collapse time of supramassive NSs for the several NS equations-of-state (EoSs) investigated. In this paper, we study four recently constructed “unified” NS EoSs (BCPM, BSk20, BSk21, and Shen) as well as three developed strange quark star (QS) EoSs within the new confinement density-dependent mass (CDDM) model, labelled as CIDDM, CDDM1, and CDDM2. All the EoSs chosen here satisfy the recent observational constraints of the two massive pulsars of which the masses are precisely measured. We construct sequences of rigidly rotating NS/QS configurations with increasing spinning frequency f, from nonrotating ($f = 0$) to the Keplerian frequency ($f = f_{\mathrm{K}}$), and provide convenient analytical parametrizations of the results. Assuming that the cosmological NS-NS merger systems have the same mass distribution as the Galactic NS-NS systems, we demonstrate that all except the BCPM NS EoS can reproduce the current 22% supramassive NS/QS fraction constraint as derived from the SGRB data. We simultaneously simulate the observed quantities (the break time t_b, the break time luminosity L_b, and the total energy in the electromagnetic channel E_{total}) of SGRBs and find that, while equally well reproducing other observational constraints, QS EoSs predict a much narrower t_b distribution than that of the NS EoSs, better matching the data. We therefore suggest that the postmerger product of NS-NS mergers might be fast-rotating supramassive QSs rather than NSs.

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I. INTRODUCTION

Short gamma-ray bursts (SGRBs) are generally believed to originate from the mergers of two neutron stars (NS-NS) [1] or one NS and one black hole (BH) (NS-BH) [2]. The nature of their central engine, however, remains unknown. Recent *Swift* observations showed extended central engine activities in the early x-ray afterglow phase [3], in particular the so-called “internal plateau,” characterized a nearly flat light curve plateau extending to ~ 300 sec followed by a rapid $t^{-(8\sim 9)}$ decay [4,5]. Since it is very difficult for a BH engine to power such a plateau, one attractive interpretation is that NS-NS mergers produce a rapidly spinning, supramassive NS [6], with the rapid decay phase signifying the epoch when the star collapses to a BH after it spins down due to dipole radiation or gravitational wave (GW) radiation [7–9]. Whether the current NS modelling could reproduce reasonably all three observed quantities [the break time t_b (or the collapse time), the break time luminosity L_b, and the total energy in the electromagnetic channel E_{total}] is crucially related to the underlying equation of state (EoS) of dense nuclear matter.

Previous studies showed that some EoS could qualitatively satisfy the observational constraints for individual SGRBs [10] and large samples [4,7]. This justifies and also demands further studies on constraining nuclear matter EoSs from SGRB data. Especially, the recent developments of many-body methods in nuclear physics have enabled a unified treatment [11–13] of all parts of the NS (the outer crust, the inner crust, and the core). All the NS EoSs applied so far in the SGRB studies [10], however, have been obtained by combing two or three EoSs that handle different density regions of the star, respectively. The matching details at the crust-core interface introduce uncertainties on model calculations [14]. Therefore, it is essential to use unified NS EoSs to properly address the NS central engine problem of SGRB.

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On the other hand, the possibility of a *bare* quark star (QS), made entirely of deconfined u, d, s quark matter [15], to serve as a the central engine of gamma-ray bursts (GRBs) has also been discussed by various authors in the past [16]. A recent analysis [17] also suggests that the conversion of NSs to QSs is crucial for both SGRBs and long GRBs in the two-families scenario of compact stars, since the well-known demanding hyperon puzzle [18] might be a challenge for the existence of massive NSs as heavy as the recent two precisely measured 2-solar-mass pulsars [19]. We therefore include in the present study the intriguing possibility of a QS engine. In particular, it would be interesting to see whether the observed narrow t_b distribution may be accounted for in the developed QS EoSs, since NS models could not [7,9]. Also, a relatively large ellipticity distribution obtained for NSs [7] is worth further investigation, although it might be explained by the distorting of the inferred strong magnetic fields [20].

Above all, it is possible to test the proposed postmerger supramassive NS/QS SGRB central engine model with unprecedented accuracy. In this paper, we perform such calculations of rotating NSs and QSs up to their mass-shedding (Keplerian) frequency, by solving exactly the widely tested *rns* code [21] and confronting these EoSs with the SGRB data.

II. NS EOS MODEL

The employed unified NS EoSs (BCPM [11], BSk20, BSk21 [12], and Shen [13]) are derived from various many-body frameworks and cover approximately the full range of high-density models regarding their stellar properties (collected in the first four rows of Table I). All unified NS EoSs can describe consistently the overall NS structure, which has been quite a challenge due to the difficulties in incorporating additional interactions of the crustal inhomogeneous phase based on nuclear many-body calculations of the core homogeneous matter.

The BCPM EoS, named after Barcelona-Catania-Paris-Madrid, is based on one of the most advanced microscopic approaches, the Brueckner-Hartree-Fock (BHF) theory [22]. The BSk20 and BSk21 EoSs belong to the BSk family of Skyrme nuclear effective forces derived by the Brussels-Montreal group [12]. The high-density part of the two are adjusted to the results of the variational method and the BHF calculations, respectively. The widely used Shen EoS [13] is based on a phenomenological nuclear relativistic mean field model with the TM1 parameter set.

III. QS EOS MODEL

The possible existence of QSs [15] originates from a hypothesis back in the early 1970s [23], namely that strange quark matter could be the absolute ground state of matter at zero pressure and temperature. It has inspired extensive discussions from its detailed phase structures [24] and its relevance to various high-energy transient aspects of astronomy, such as GRBs [16], x-ray bursters [25], super-luminous supernovae [26], and radio pulsars [27].

Although a first-principle calculation in such systems is unachievable due to the complicated nonlinear and non-perturbative nature of QCD (see Ref. [28] for recent progress in perturbative QCD and powerful modeling of QCD in the perturbative and nonperturbative domain using Dyson-Schwinger equations), a comprehensive set of proposed quark-matter EoS [29,30] has been proposed lately with the basic QCD spirits built in. In the recent version of the confined-density-dependent-mass (CDDM) model [29], the quark confinement is achieved by the density dependence of the quark masses derived from in-medium chiral condensates, and leading-order perturbative interactions have been included. Such terms become dominant at high densities and can lead to absolutely stable strange quark matter and a massive QS made of such matter as heavy as 2 solar mass [19]. In the present calculation, we employ three typical cases of the CDDM QS EoSs [29] (labelled as CIDDM, CDDM1, and CDDM2) instead of the simple MIT model [31]. The corresponding static QS properties are shown in the last three rows of Table I. We mention here that the MIT QS EoSs model [31] allows a more compact QS with $R_{\rm eq} \sim 11.5$ km.

TABLE I. NS/QS EoSs investigated in this study. Here, $P_{\rm K}$ and $I_{\rm K,max}$ are the Keplerian spin limit and the corresponding maximum moment of inertia, respectively; $M_{\rm TOV}$ and $R_{\rm eq}$ are the static gravitational maximum mass by integrating the Tolman-Oppenheimer-Volkoff (TOV) equations and the corresponding equatorial radius, respectively; α, β are the fitting parameters for $M_{\rm max}$ in Eq. (1); A, B, C are the fitting parameters for $R_{\rm eq}$ in Eq. (2); and a, q, k are the fitting parameters for $I_{\rm max}$ in Eq. (3).

	EoS	$P_{\rm K}$ (ms)	$I_{\rm K,max}$ (10^{45} g cm^2)	$M_{\rm TOV}$ ($M_\odot$)	$R_{\rm eq}$ (km)	α ($P^{-\beta}$)	β	A (P^{-B})	B	C (km)	a	q (ms)	k (P^{-1})
NS	BCPM	0.5584	2.857	1.98	9.941	0.038 59	−2.651	0.7172	−2.674	9.910	0.4509	0.3877	7.334
	BSk20	0.5391	3.503	2.17	10.17	0.035 87	−2.675	0.6347	−2.638	10.18	0.4714	0.4062	6.929
	BSk21	0.6021	4.368	2.28	11.08	0.048 68	−2.746	0.9429	−2.696	11.03	0.4838	0.3500	7.085
	Shen	0.7143	4.675	2.18	12.40	0.076 57	−2.738	1.393	−3.431	12.47	0.4102	0.5725	8.644
QS	CIDDM	0.8326	8.645	2.09	12.43	0.161 46	−4.932	2.583	−5.223	12.75	0.4433	0.8079	80.76
	CDDM1	0.9960	11.67	2.21	13.99	0.391 54	−4.999	7.920	−5.322	14.32	0.4253	0.9608	57.94
	CDDM2	1.1249	16.34	2.45	15.76	0.744 77	−5.175	17.27	−5.479	16.13	0.4205	1.087	55.14

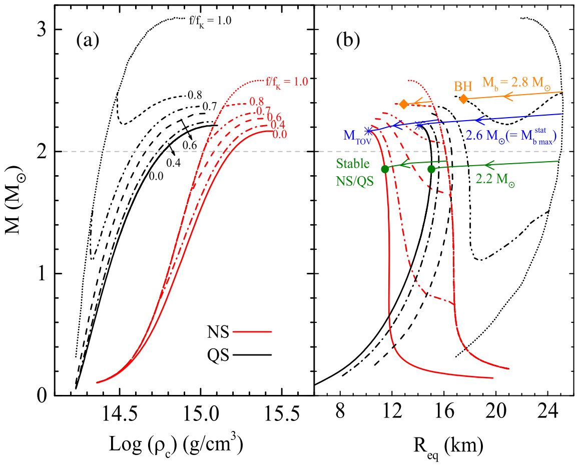

FIG. 1. Gravitational mass M vs central energy density ρ_c (panel a) and radius (panel b), for six cases of frequency: $f/f_K = 0$, 0.4, 0.6, 0.7, 0.8, 1. Solid lines with arrows denote sequences of constant baryon mass. The NS (QS) results are obtained using the BSk20 (CDDM1) EoS.

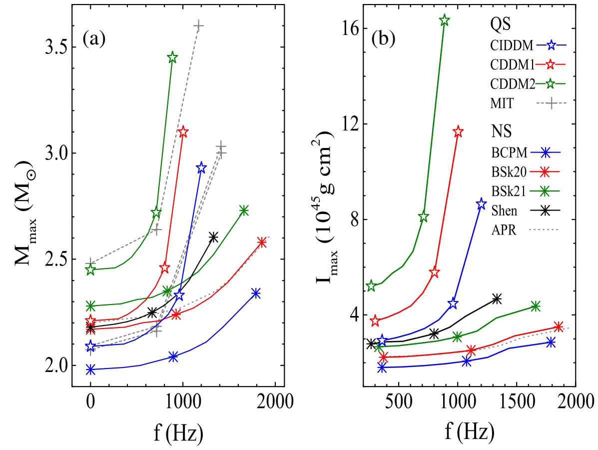

FIG. 2. Maximum gravitational mass $M_{\rm max}$ (panel a) and maximum moment of inertia $I_{\rm max}$ (panel b) as a function of the spin frequency, for three cases of QS EoSs (CIDDM, CDDM1, and CDDM2) and four cases of unified NS EoSs (BCPM, BSk20, BSk21, and Shen). Previous calculations using the APR NS EoS model [10] and the MIT QS EoS model [31] are also shown for comparison.

IV. ROTATING NS/QS CONFIGURATIONS

For a given EoS, the *rns* code presents uniformly rotating, axisymmetric configurations of a NS/QS. We show them in Fig. 1 for two representative EoSs (BSk20 for NSs in red and CDDM1 for QSs in black) from the nonrotating cases ($f = 0$) to the Keplerian frequency case ($f = f_K$).

We can see that rotation increases the mass that a star of given central density can support. As a consequence, the static configuration with the baryon mass $M_b > M^{\rm stat}_{\rm b,max}$ does not exist (in the two EoS models shown in Fig. 1, $M^{\rm stat}_{\rm b,max} \sim 2.6\ M_\odot$). Such sequences are so-called *supramassive* stars which exist only by virtue of rotation. Those are the ones we are interested in as their spindown-induced collapse to BHs [orange curves in Fig. 1(b)] would manifest themselves as the rapid decay in x-ray luminosity at the end of the plateau. The star sequences of $M_b \leq M^{\rm stat}_{\rm b,max}$ [blue and green curves in Fig. 1(b)] instead would evolve to its static configurations with the same baryon masses as they spin down. Rotation also increases both the equatorial radius and certainly the moment of inertia.

In Fig. 2, the maximum mass and the maximum moment of inertia are shown as a function of the spin frequency for both NS and QS EoSs. Previous calculations using the APR NS EoS model [10] and the MIT QS EoS model [31] are also shown for comparison. All QS EoS models have similar behaviors but are quite different with various NS EoS models. The $M_{\rm max}$ values for the chosen NS (QS) EoSs are roughly 18%–20% (~40%) higher than the nonrotating maximum mass $M_{\rm TOV}$. The corresponding increase in $R_{\rm eq}$ is 31%–36% (57%–60%). Evidently, the increases of ($M_{\rm max}$, $R_{\rm eq}$, $I_{\rm max}$) are more pronounced with the QS EoSs than those with the NS ones. We shall soon see that this leads to one main conclusion of the present study that a QS central engine model is more preferred than a NS one.

For later use, we find that the calculations of $M_{\rm max}$, $R_{\rm eq}$, and $I_{\rm max}$ can be fitted well as a function of the spin period (P) (in milliseconds) as follows,

$$\frac{M_{\rm max}}{M_\odot} = \frac{M_{\rm TOV}}{M_\odot}\left[1 + \alpha\left(\frac{P}{\rm ms}\right)^{\beta}\right]; \qquad (1)$$

$$\frac{R_{\rm eq}}{\rm km} = C + A\left(\frac{P}{\rm ms}\right)^{B}; \qquad (2)$$

$$\frac{I_{\rm max}}{10^{45}\ {\rm g\,cm^2}} = \frac{M_{\rm max}}{M_\odot}\left(\frac{R_{\rm eq}}{\rm km}\right)^2 \frac{a}{1 + e^{-k(\frac{P}{\rm ms} - q)}}, \qquad (3)$$

where the parameters (α, β, A, B, C, a, q, k) are collected in the last eight columns of Table I.

V. SUPRAMASSIVE NS/QS FRACTION

A previous study [4] has identified 21 candidates for supramassive stars (i.e., those bursts with internal plateaus) in 96 SGRBs detected by Swift up to October 2015. Therefore, the current fraction is ~22%. Before comparing our results with detailed SGRB observations, it is necessary to first check if the chosen NS/QS EoSs could reproduce such a faction in NS-NS merger products. Such a test is possible if one assumes that the cosmological NS-NS merger systems have the same mass distribution as the Galactic NS-NS binary systems. A distribution of $M = 2.46^{+0.13}_{-0.15} M_\odot$ was worked out [10] for the gravitational mass of the postmerger supramassive stars.

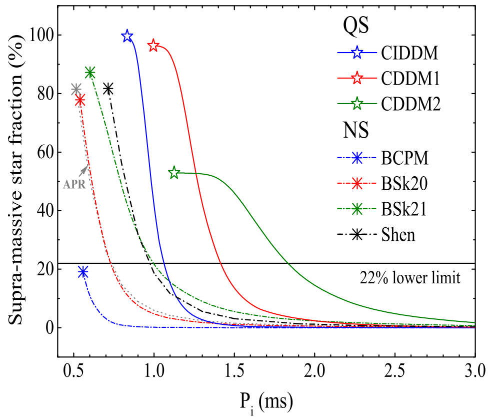

FIG. 3. Theoretical estimations of the supramassive star fraction based on four cases of unified NS EoSs and three cases of QS EoSs, as compared with the observed 22% constraint. Previous calculations [7] using the APR NS EoS model are also shown for comparison.

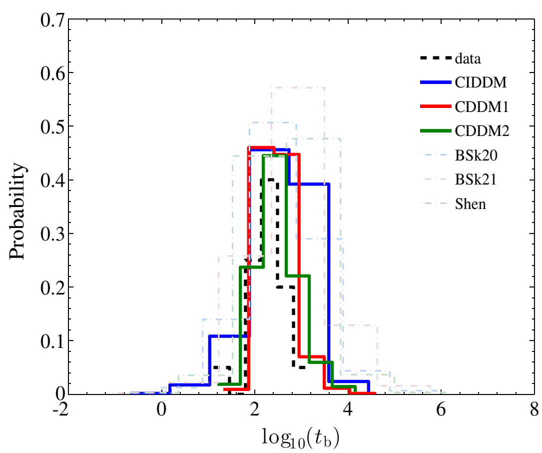

FIG. 4. Simulated collapse time distributions with three unified NS EoSs and three QS EoSs, as compared with the observed one (dashed curve).

We theoretically calculate, for any given initial spin period $P_i \le P_K$, the upper bound M_{sup} for the mass of the supramassive NS/QS, by solving $[(M_{sup} - M_{TOV})/(\alpha M_{TOV})]^{1/\beta} = P_i$ deduced in the last section. Setting the lower bound as the nonrotating maximum mass M_{TOV}, we can finally evaluate the supramassive NS/QS fraction based on the $M = 2.46^{+0.13}_{-0.15} M_\odot$ mass distribution [10]. This is done for all employed NS/QS EoSs. The results are shown in Fig. 3. One can see that all except the BCPM NS EoS can reproduce the 22% fraction constraint (with slightly different required P_i). In the following, we omit the BCPM EoS.

VI. COLLAPSE TIME SIMULATION OF SUPRAMASSIVE NSS/QSS

Previously, when confronting Swift observations of the internal plateaus sample with several matched NS EoSs [10], Ravi and & Lasky [9] and Gao *et al.* [7] found that, although the star parameters can be reasonably constrained, the predicted break time t_b of NSs is always too wide compared with the data. In this section, we apply our previous Monte Carlo simulations [7] to the new EoSs for both NSs and QSs studied in this paper. The results are shown in Fig. 4 and Table II.

By requiring that the P values of the Kolmogorov-Smirnov (KS) tests of all three distributions (t_b, L_b, and E_{total}) are larger than 0.05 as the criteria for reproducing the observations, we list the constrained ranges for the NSs'(QSs') parameters: an ellipticity ϵ as low as 0.002 (0.001), an initial spin period P_i commonly close to the Keplerian limit P_K, a surface dipole magnetic field of $B_p \sim 10^{15}$ G, and an efficiency of $\eta = 0.5$–1 related to the conversion of the dipole spindown luminosity to the observed x-ray luminosity. The results with the best P values for the KS tests are listed in brackets. In the last column, we show $P_{best}(t_b)$, the best values only for the t_b distribution. It is clear that the KS test for the t_b distribution is indeed improved from Ref. [7]. In particular, as one can see from Fig. 4, the t_b distributions in the QS scenarios are more concentrated, which provides a better agreement with the observed ones. The required P_i for QSs is also larger (longer than 1 ms), which is consistent with the recent numerical simulations of NS-NS mergers that show a significant GW is released during the merger phase [32]. Also, a slightly lower and more

TABLE II. Simulated parameter ranges for supramassive NS/QS properties from the Swift internal plateaus sample with EoS models (except BCPM) from Table I. Here, ϵ, P_i, B_p, and η are the ellipticity, the initial spin period, the surface dipole magnetic field, and the radiation efficiency, respectively. Data in brackets are those with the best KS tests. $P_{best}(t_b)$ in the last column is the best P value only for the t_b distribution.

EoS	ϵ	P_i (ms)	$B_p(G)$	η	$P_{best}(t_b)$
BSk20	0.002	0.70–0.75 (0.75)	$N(\mu_{Bp} = 10^{14.8-15.4}, \sigma_{Bp} \le 0.2)[N(\mu_{Bp} = 10^{14.9}, \sigma_{Bp} = 0.2)]$	0.5–1 (0.9)	0.20
BSk21	0.002	0.60–0.80 (0.70)	$N(\mu_{Bp} = 10^{14.7-15.1}, \sigma_{Bp} \le 0.2)[N(\mu_{Bp} = 10^{15.0}, \sigma_{Bp} = 0.2)]$	0.7–1 (0.9)	0.29
Shen	0.002–0.003 (0.002)	0.70–0.90 (0.70)	$N(\mu_{Bp} = 10^{14.6-15.0}, \sigma_{Bp} \le 0.2)[N(\mu_{Bp} = 10^{14.6}, \sigma_{Bp} = 0.2)]$	0.5–1 (0.9)	0.41
CIDDM	0.001	0.95–1.05 (0.95)	$N(\mu_{Bp} = 10^{14.8-15.4}, \sigma_{Bp} \le 0.2)[N(\mu_{Bp} = 10^{15.0}, \sigma_{Bp} = 0.2)]$	0.5–1 (0.5)	0.44
CDDM1	0.002–0.003 (0.003)	1.00–1.40 (1.0)	$N(\mu_{Bp} = 10^{14.7-15.1}, \sigma_{Bp} \le 0.3)[N(\mu_{Bp} = 10^{14.7}, \sigma_{Bp} = 0.2)]$	0.5–1 (1)	0.65
CDDM2	0.004–0.007 (0.005)	1.10–1.70 (1.3)	$N(\mu_{Bp} = 10^{14.8-15.3}, \sigma_{Bp} \le 0.4)[N(\mu_{Bp} = 10^{14.9}, \sigma_{Bp} = 0.4)]$	0.5–1 (1)	0.84

reasonable magnetic-field-induced ellipticity obtained for QSs is justified by the fact that QSs are more susceptible to magnetic field deformations than NSs [33]. We therefore argue that a supramassive QS is favored over a supramassive NS to serve as the central engine of SGRBs with internal plateaus [34].

VII. SUMMARY

To recap, we have carried out the following investigations: 1) selecting unified NS EoSs that satisfy up-to-date experimental constraints from both nuclear physics and astrophysics, based on modern nuclear many-body theories; 2) finding typical parameter sets for QS EoSs in the developed CDDM model, under the same constraints of the NS case for the high-density part; 3) accurately solving the fast-rotating configurations of both NSs and QSs and providing convenient analytical parametrizations of the results; 4) checking whether the employed EoSs can fulfill the observed fraction of supramassive stars, based on the mass distribution observation of Galactic NS-NS binary systems; and 5) simulating observed properties of the SGRB internal plateaus sample and revealing the postmerger supramassive stars' physics. We finally reach the conclusion that the postmerger products of NS-NS mergers are probably supramassive QSs rather than NSs. NS-NS mergers are a plausible location for quark deconfinement and the formation of QSs.

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