THE NEWLY BORN MAGNETARS POWERING GAMMA-RAY BURST INTERNAL-PLATEAU EMISSION: ARE THERE STRANGE STARS?

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ABSTRACT

The internal-plateau X-ray emission of gamma-ray bursts (GRBs) indicates that a newly born magnetar could be the central object of some GRBs. The observed luminosity and duration of the plateaus suggest that, for such a magnetar, a rapid spin with a sub- or millisecond period is sometimes able to last thousands of seconds. In this case, the conventional neutron star (NS) model for the magnetar may be challenged, since the rapid spin of nascent NSs would be remarkably decelerated within hundreds of seconds due to $r$-mode instability. In contrast, the $r$-modes can be effectively suppressed in nascent strange stars (SSs). In other words, to a certain extent, only SSs can keep nearly constant extremely rapid spin for a long period of time during the early ages of the stars. We thus propose that the sample of the GRB rapidly spinning magnetars can be used to test the SS hypothesis based on the distinct spin limits of NSs and SSs.

Key words: gamma rays: bursts – stars: neutron

1. INTRODUCTION

In the standard fireball model for gamma-ray bursts (GRBs; see reviews by Piran 2005; Mészáros 2006), the GRB prompt emission is considered to arise from an internal dissipation in a relativistic expanding fireball, while the afterglow emission is produced by the deceleration of the fireball by circumburst medium, i.e., a blast wave. As understood above, it seems unlikely to directly find information about the GRB central engine, which drives the fireball, from the observed emission. However, based on some observational constraints and theoretical simulations, it is widely accepted that black holes or rapidly spinning magnetars (highly magnetized pulsars) formed during the death of the progenitors play an important role in driving the fireball. Furthermore, the Swift-discovered delayed intermittent bright X-ray flares demonstrate that the GRB central objects should be still very active after the bursts (Burrows et al. 2005; Yu & Dai 2009). Analogically, the shallow-decaying segment remarkably appearing in the canonical X-ray light curve (Nousek et al. 2006; Zhang et al. 2006) also strongly implies an energy injection into the GRB blast waves, which is quite likely to result from a long-lasting energy release from the central objects. Under these requirements, spinning-down magnetars are usually suggested as GRB central objects in the literature (e.g., Bucciantini et al. 2009; Corsi & Mészáros 2009; Dai 2004; Dai et al. 2006; De Pasquale et al. 2007; Zhang & Dai 2008, 2009). The shallow-decaying afterglows can somewhat be regarded as an observational signature of rapidly spinning magnetars (Dai & Lu 1998a, 1998b; Yu & Dai 2007; Zhang & Mészáros 2001).

In particular, a nearly constant X-ray emission following a very steep decline with a temporal index of $\sim 9$ was reported in GRB 070110 by Troja et al. (2007). The abrupt cutoff of the X-ray light curve robustly indicates that this plateau emission is of “internal” origin, ruling out the external shock model. Moreover, the observed luminosity and duration of the plateau are well consistent with the parameters of a newly born magnetar. So, following Zhang & Mészáros (2001), Troja et al. (2007) further argued that this puzzling plateau could be directly produced by the internal dissipation of the magnetar-driven wind at small radii, before the energy of the wind is deposited into the GRB blast wave. Then, the observed luminosity of the plateau tracking the spin-down luminosity of the GRB magnetar makes it possible to “directly” explore the properties of the central objects by using observed emission.

As a pioneering attempt, Lyons et al. (2009) investigated the magnetic and rotational properties of the central magnetars for 10 GRB 070110-like GRBs. While the inferred magnetic field strengths are basically typical for magnetars, the spin periods are usually found to be as short as the Kepler period, sometimes even at thousands of seconds after the GRB trigger. However, for a magnetar composed of normal neutron matter (i.e., neutron star—NS), it seems difficult to keep nearly Kepler spin for more than one thousand seconds, because the spin of the nascent NS could be sorely restricted by some stellar instabilities, especially, $r$-mode instability which is the focus in this Letter (Sá 2004; Sá & Tomé 2005, 2006; Yue et al. 2009). In contrast, for a magnetar composed of strange quark matter (i.e., strange star—SS), the $r$-modes-induced limit on the stellar spin is absent during the early ages of the star because of the effective suppression of the $r$-modes by the quark matter’s bulk viscosity (e.g., Wang & Lu 1984; Madsen 1998; Zheng et al. 2006). Therefore, we argue that a newly born magnetar, which can maintain constant rapid spin for a long period of time, could be an SS candidate. Based on this consideration, we propose that the sample of the GRB rapidly spinning magnetars can be used to test the SS hypothesis.

In the following section, we briefly review the magnetar model for the internal-plateau emission, and then some magnetar parameters are derived from a small GRB sample. In Section 3, we analyze the $r$-mode limit on the spin of NSs in the framework of a second-order $r$-mode model developed by Sá (2004). By confronting the $r$-mode limit with the GRB magnetar sample, we make an attempt to find SS candidates. Finally, a summary and discussion are given in Section 4.

1 According to the different physics of dense matter, a variety of models for compact stars have been constructed in the past 40 years (see reviews by Weber 2005; Weber et al. 2006). Most of these models can be regarded as advanced versions of the conventional NS model. However, as an extreme case, SSs composed of strange quark matter (usually with a thin nuclear crust) are predicted to be completely different from ordinary NSs (e.g., Alcock et al. 1986).
2. MAGNETARS POWERING INTERNAL PLATEAUS

As discussed above, the internal-plateau emission indicates that a rapidly spinning magnetar has been formed as a central object during the prompt phase of some GRBs. The initial spin evolution of a magnetar could be very complicated during the first tens of seconds after its birth. On the longer timescales that we are interested in, some short-term processes such as neutrino-driven winds could be no longer important. Here we simply consider that the nascent magnetar spins down through magnetic dipole radiation as

$$\frac{dP}{dt} = \frac{P}{\tau_m},$$

where \(P\) is the spin period of the star. The magnetic braking timescale reads (Shapiro & Teukolsky 1983)

$$\tau_m = \frac{6c^3}{(2\pi)^2} \frac{I P^2}{B^2 R^6} = 4 \times 10^3 I_{45} R_{15}^{-6} B_{-2}^{-2} P_{-3}^2 \text{ s},$$

where \(c\) is the speed of light, and \(I, R, \) and \(B\) are the moment of inertia, the radius, and the surface magnetic field strength of the magnetar, respectively. The convention \(Q_x = Q / 10^x\) is adopted in cgs units hereafter. Equation (1) yields \(P(t) = P_i (1 + t/\tau_m)^{1/2}\), where \(P_i\) is the initial spin period and

$$T_m = P_i^2 / P^3 = \frac{1}{2} \frac{T_{m,i}}{T_p} = 2 \times 10^3 I_{45} R_{15}^{-6} B_{-2}^{-2} P_{-3}^{-3} \text{ s}.$$  

The expression of \(P(t)\) shows that a nascent magnetar only against the magnetic braking effect can keep nearly constant spin for a period of time \(T_m\). As the spinning down, the magnetar releases the spinning energy and drives an outward-propagating wind. We then approximately estimate the luminosity of the wind by the magnetically spin-down luminosity as \(L_\text{wind} \approx L_\text{msd} = (2\pi)^3 / P^3 = (\tilde{L}_1 (1 + t/\tau_m))^{-2}\) with

$$\tilde{L} \equiv \frac{(2\pi)^3 \tilde{B}^2 R^6}{P_i^4} = 10^{39} R_{15}^{3} B_{-2}^{-2} P_{-3}^{-4} \text{ erg s}^{-1}.$$  

Since the observed internal-plateau emission is deemed to be directly emitted by magnetar winds, the model quantities \(L\) and \(T_m\) can be easily determined by the observational isotropically equivalent luminosity \(L_{\gamma, \text{iso}}\) and the observational duration \(T_p\) of the plateaus as follows:

$$\tilde{L} \geq L_{\gamma, \text{iso}}, T_m \geq T_p = \frac{T_{p, \text{obs}}}{(1 + z)},$$

where \(z\) is the redshift of the GRBs. The beaming factor \(f_b = (1 - \cos \theta_w)\), with \(\theta_w\) being the half-opening angle of the winds, is introduced because the magnetar winds could be collimated rather than perfectly isotropic (Bucciantini et al. 2007; Lyons et al. 2009). By solving Equation (5), the magnetic field strengths and the initial spin periods of the GRB magnetars can be derived as

$$B \leq 2 \times 10^{15} I_{45} R_{15}^{-6} L_{\gamma, 49, \text{iso}}^{-1/2} T_{p, \text{iso}}^{-1} \text{ G},$$

$$P_i \leq 1.4 \times 10^{-3} I_{45}^{1/2} L_{\gamma, 49, \text{iso}}^{-1/2} T_{p, \text{iso}}^{-1/2} \text{ s}.$$  

The greater-than and less-than signs appear in Equations (5)–(7) because the radiation efficiency of the winds should be lower than 100% and the cutoff of the plateaus could be caused by a rapid decrease of the stellar magnetic fields (Troja et al. 2007) or by a collapse of the magnetars into black holes (Lyons et al. 2009). In this Letter, for simplicity, we consider only the case of equality for Equations (6) and (7) as an extreme case, as did Lyons et al. (2009).

In order to conveniently estimate the values of \(B\) and \(P_i\) for specific GRBs in the \(\lg L_{\gamma, \text{p}} - \lg T_p\) panel, in Figure 1 we plot a set of dashed lines for different values of \(B\) and a set of dotted lines for different values of \(P_i\), which are, respectively, determined by

$$\lg L_{\gamma, 49} = -2 \lg T_{p, 3} + (0.6 - 2 \lg B_{15}),$$  

$$\lg L_{\gamma, 49} = -\lg T_{p, 3} + (0.3 - 2 \lg P_i, 3),$$

where a typical value of unit is adopted for \(I_{45}\) and \(R_6\) in view of the sufficiently small variations of these parameters. For a realistic magnetar, its rotation obviously cannot be faster than the Kepler rotation, at which the star starts shedding mass at the equator. So an absolute upper limit on the spin periods of magnetars is given by the Kepler period (Haensel et al. 2009)

$$P_K = C \left( \frac{M}{1.4 \, M_\odot} \right)^{-1/2} R_6^{3/2} \text{ s},$$

where \(M\) is the gravitational mass of the magnetar. For the prefactor \(C\), the careful numerical calculation given by Haensel et al. (2009) showed that its value is slightly dependent on the equation of state of the stellar matter, specifically, \(C = 0.783 \text{ ms for NSs and } 0.735 \text{ ms for SSs}\). For a conservative discussion, we simply take \(C = 0.8 \text{ ms for both NSs and SSs as proposed by Lattimer & Prakash (2004).}\)

In Figure 1, we also scatter the observational internal-plateau data of 10 GRBs as listed in Table 1, which survived from an internal-plateau test in Lyons et al. (2009) with three criteria: (1) the X-ray light curve could not be adequately fitted by the Willingale model (Willingale et al. 2007); (2) a relatively constant X-ray flux lasts for a significant period of time; and
(3) the plateau is followed by a convincing steep decline with a temporal index $> 4$, so that the internal origin of the plateau is favored. Under the isotropic assumption for the magnetar winds, the data (open circles) are obviously in contradiction with the Friedman–Schutz instability (Chandrasekhar 1970; Friedman & Schutz 1978). As a result, the rapid spin of newly born NSs undoubtedly, no matter whether the star is an NS or an SS succumbing to gravitational radiation-driven Chandrasekhar–Schutz instability (Chandrasekhar 1970; Friedman & Schutz 1978). As a result, the rapid spin of newly born NSs can be reduced early and remarkably by the strong gravitational radiation, but cannot for nascent SSs. Then, the question arises as to whether the GRB rapidly spinning magnetars are NSs or SSs, or whether we can find SS candidates from GRB magnetars. Following a phenomenological model for $r$-modes proposed by Sá (2004), the evolution of the amplitude of the $r$-mode oscillation, $\alpha$, can be calculated from (Owen et al. 1998; Sá & Tomé 2005; Yu et al. 2009).

$$\frac{d\alpha}{dt} = \left[ 1 + \frac{2\alpha^2}{15}(\delta + 2) \right] \frac{\alpha}{\tau_g} - \left[ 1 + \frac{\alpha^2}{30}(4\delta + 5) \right] \frac{\alpha}{\tau_g} \frac{\alpha}{2\tau_m}, \quad (11)$$

where $\delta$ is a free parameter describing the initial degree of the differential rotation of a nascent magnetar, $\tau_g = 3T(\Pi/P_K)^6$ s (12) is the gravitational radiation timescale, and $\tau_v = (\tau_{sv}^{-1} + \tau_{sv}^{-1})^{-1}$ is the viscous damping timescale with $\tau_{sv}$ and $\tau_{sv}$ corresponding to the shear and bulk viscosities, respectively. Accordingly, the spin-down of the magnetar against both gravitational and magnetic braking effects is determined by

$$\frac{dP}{dt} = \frac{4\alpha^2}{15}(\delta + 2) \frac{P}{\tau_g} - \frac{\alpha^2}{15}(4\delta + 5) \frac{P}{\tau_v} + \frac{P}{\tau_m}. \quad (13)$$

In the case of $\tau_g \gg \tau_m$ where the $r$-modes cannot arise sufficiently rapidly, the above equation can be well approximated by Equation (1). In contrast, for $\tau_g \ll \tau_m$, the spin-down is instead dominated by the gravitational braking, if the $r$-mode amplitude can reach its saturated value in time under a condition of $\tau_g \ll \tau_m$. However, the value of $\tau_g$ is sensitive to the properties of the stellar matter.

To be specific, we display the viscous damping timescales for an NS and an SS, respectively, as (Owen et al. 1998; Madsen 2000)$^2$

$$\tau_{sv}^{NS} \approx 2.52 \times 10^{10} T_{10}^{2} \text{ s}, \quad (14)$$

$$\tau_{sv}^{SS} \approx 1.57 \times 10^{3} T_{10}^{6} (P/P_K)^3 \text{ s}, \quad (15)$$

$$\tau_{sv}^{SS} \approx 2.49 \times 10^{10} T_{10}^{5/3} \text{ s}, \quad (16)$$

$$\tau_{sv}^{SS} \approx 0.02 T_{10}^{12} (P/P_K)^2 \text{ s}. \quad (17)$$

where $T$ is the stellar temperature. For a nascent magnetar with $T = T_{i} \approx 10^8$ K and $P = P_{i} \approx P_K$, on one hand, the shear viscous damping of the $r$-modes can be neglected undoubtedly, no matter whether the star is an NS or an SS due to $\tau_{sv} \gg (\tau_g, \tau_m, \tau_{sv}, \tau_{sv})$. On the other hand, the significant difference between $\tau_{sv}^{NS} (\gg \tau_g)$ and $\tau_{sv}^{SS} (\ll \tau_g)$ would lead to two distinct results, (1) For a nascent SS, the $r$-mode instability is suppressed effectively by the bulk viscosity. By equating $\tau_g$ to $\tau_{sv}^{SS}$ to get $T_{10} \approx 0.2$ and following the direct-Urca-process-dominated cooling $T = T_1 (1 + t/\tau_{sv})^{-1/4}$ with $\tau_g \sim 1$ s, we can find that it should take about $\sim 10^7$ s to achieve $\tau_g \approx \tau_{sv}^{SS}$ at which $r$-modes can arise. During this long period of time of $\sim 10^7$ s, the spin-down of the SS is exclusively dominated by the relatively stronger magnetic dipole radiation (Zheng et al. 2006). Therefore, the upper limit of the spin periods of nascent SSs can be simply set at the Kepler period. (2) In contrast, for nascent NSs, $r$-modes can arise rapidly and arrive at its saturated amplitude within hundreds of seconds (Sá & Tomé 2005, 2006). As a result, the spin-down of the NSs would be first dominated by the gravitational braking, much before the magnetic braking operates (Yu et al. 2009).

Now let us investigate how long a nascent NS against $r$-mode instability can keep constant spin with $\tau_g \ll \tau_m$.

\begin{table}[h]
\centering
\caption{The Observed Properties of the Internal Plateaus of 10 GRBs$^a$}
\begin{tabular}{lcccc}
\hline
GRB & $L_{\gamma,\text{iso}}$ (erg s$^{-1}$) & $T_{\rho}^{\text{iso}}$ (s) & $z$ & $T_{\rho}$ (s) \\
\hline
080310 & 2.6e+50 & 401.9 & 2.426 & 117.3 \\
071021 & 6.6e+50 & 248.3 & 5.0 & 41.4 \\
070721B & 3.0e+49 & 802.9 & 3.626 & 173.6 \\
060616 & 4.4e+50 & 585.6 & 2.22 & 181.9 \\
070129 & 8.6e+49 & 683.0 & 2.22 & 212.1 \\
070110 & 8.6e+47 & 21887.1 & 2.352 & 6529.6 \\
060607A & 1.3e+49 & 13294.7 & 3.082 & 3256.9 \\
060510B & 1.7e+51 & 362.9 & 4.9 & 61.5 \\
060202 & 1.0e+50 & 766.0 & 2.22 & 237.9 \\
050904 & 7.1e+50 & 488.8 & 6.29 & 67.1 \\
\hline
\end{tabular}
\end{table}

Note. $^a$ See Lyons et al. (2009) for a detailed explanation of the data.

$^2$ The viscous timescales of the SS presented here are obtained for a normal quark matter phase. More generally, some color superconducting phases such as the two-flavor color superconductivity and color-flavor-locked phases have also been suggested for sufficiently high density and sufficiently low temperature (see a recent review by Alford et al. 2008). In these phases, the viscosities of the quark matter can be changed (generally reduced) significantly. However, at high temperatures of $\sim 10^{10}$–$10^{11}$ K as in nascent magnetars concerned in this Letter, the bulk viscosity of the superconducting matter could be still comparable to that of the unpaired quark matter (e.g., Alford & Schmitt 2007).
convenience, we here exhibit an asymptotic solution as (Sá & Tomé 2005, 2006)

\[
P(t) \approx \begin{cases} 
P_i \left[ 1 - \frac{2\alpha_i}{15}(\delta + 2) \exp\left( \frac{2\alpha_i}{15} \right) \right]^{-1}, & \text{for } t < T_g \\
1.6 P_i \left( \frac{1}{\tau_g} \right)^{1/5}, & \text{for } t > T_g, 
\end{cases}
\]

where \( \alpha_i \) is the initial \( r \)-mode amplitude. The break time \( T_g \) can be solved from \( \alpha_i = 0 \) to be

\[
T_g = -37 \left[ \ln \alpha_i + \frac{1}{2} \ln(\delta + 2) + \frac{1}{2} \ln \frac{6}{5} \left( \frac{P_i}{P_K} \right)^6 \right],
\]

at which \( P = 1.125 P_i \). After \( T_g \), the spin period of the NS can no longer be regarded as a constant and the luminosity of the wind evolves as \( L_w \approx L_{\text{mod}} \propto t^{-4/5} \), which obviously deviates from a plateau emission. So we conclude that a nascent NS with an initial period \( P_i \) can keep nearly constant spin for at most a period of time of \( T_g(P_i) \). For \( P_i = P_K \), we have \( T_g = T_K \). Within a wide parameter region of \( 10^{-10} < \alpha_i < 10^{-6} \) and \( 0 < \delta < 10^3 \) (Sá & Tomé 2005, 2006), the value of \( T_K \) varies from 170 s to 840 s.

Therefore, for GRB magnetars with \( T_p > 10^3 \) s, it is necessary to test whether their spin is sufficiently slow to determine a sufficiently long \( T_g \) as

\[
P_i < P_R = P_K(T_p/T_K)^{1/6}.
\]

If not, the magnetar is quiet unlikely to be an NS. Alternatively, it could be an SS candidate. Substituting Equation (20) into (9) with \( P_K = 0.8 \), we can obtain

\[
\log L_{\gamma,b,49} = -4/3 \log T_{p,3} + \left( -0.5 + 1/3 \log T_K \right).
\]

With a certain value of the free parameter \( T_K \), this equation determines an \( r \)-mode limit line for NSs in the \( \log L_{\gamma,b} - \log T_p \) panel, as shown by the solid lines in Figure 2, above which \( T_p > T_g \).

Then a special region below the Kepler limit line and above the \( r \)-mode limit line is highlighted in the \( \log L_{\gamma,b} - \log T_p \) panel, where only SSs can appear. When we use this SS-only region to cover the observational GRB internal-plateau data, we can obtain that either (1) some SS candidates are indicated by the data locating in the SS-only region, or (2) all data are clearly below the \( r \)-mode limit line. In the latter case, in principle, the SS model cannot be ruled out, but the influence of the gravitational-driven \( r \)-mode instability on the spin of NSs would be confirmed. For the small sample of GRB magnetars listed in Table 1, we find in Figure 2 that GRB 060607A is located just above the \( r \)-mode limit line, by assuming the fastest possible period as the Kepler period (\( \theta_w = 45^\circ \)) and taking \( T_K = 170 \) s. This implies that the magnetar in GRB 060607A could be an SS. It is fair to say, though, that the uncertainties and approximations involved could be large enough that the NS model still might be available for this magnetar. So a much richer GRB sample is sorely demanded in order to get a more definite conclusion.

4. SUMMARY AND DISCUSSION

The internal-plateau emission is considered to indicate that a central rapidly spinning magnetar is formed during some GRBs. Such a newly born magnetar is sometimes required to be able to keep a rapid spin with a sub- or millisecond period for thousands of seconds. Then, according to the spin limit of nascent NSs due to \( r \)-mode instability, we propose a method to identify SS candidates from the GRB magnetars since the \( r \)-mode instability cannot operate in nascent SSs. Despite the smallness of the present GRB magnetar sample, the effectiveness of the method is somewhat exhibited by the appearance of GRB 060607A.

A few decades ago, the concept of SSs was proposed formerly as a new and novel class of compact stars (Alcock et al. 1986; Haensel et al. 1986) and even as GRB central objects (Cheng & Dai 1996, 1998; Dai & Lu 1998a), based on a conjecture that the true ground state of matter is strange quark matter rather than Fe\(^{56}\) (Witten 1984). In both physics and astronomy, it is of significant importance to identify or rule out SSs from observational astrophysical objects. Seasonably, a plausible method was designed by Madsen (1998) according to the distinct rotational properties of NSs and SSs against the \( r \)-mode instability. However, for most detected Galactic millisecond pulsars, the stellar temperature is generally much lower than \( \sim 10^{10} \) K, in which case some complications arise from the shear viscosity due to the stellar crust (e.g., Bildsten & Ushomirsky 2000) and the superfluidity appearing in the stellar core. This makes it difficult to distinguish SSs from NSs within the Galactic pulsar sample (Madsen 2000). In contrast, the situation in newly born pulsars would be much clearer due to their sufficiently high temperature. Moreover, for GRB magnetars, a relatively richer sample could be selected from the huge GRB storage, in contrast to the rare observation of newly born pulsars in the Galaxy. In view of these advantages, it is worthwhile to use the newly born GRB magnetars to test the SS hypothesis.

However, it should be noted that the uncertainties and approximations of the model still prohibit the present small GRB magnetar sample from becoming a gold sample for testing the SS hypothesis. Therefore, it is necessary to make great efforts in the following ways. (1) A thorough investigation on magnetar wind. Here we would like to point out that the angle of the magnetar wind is probably different from that of the GRB ejecta, in that the
GRB ejecta could be driven by hyperaccretion onto the magnetar rather than the magnetar wind (Zhang & Dai 2008, 2009). (2) Finding other constraints on the wind angle. For example, in order to build up sufficient dynamo action responsible for the intense magnetic fields, the initial spin periods of magnetars could be required to be \( \leq 10 \) ms (Lyons et al. 2009; Usov 1992), which leads to \( \theta_w > 16^\circ \). (3) Accumulating a much larger number of GRB magnetars.

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