Signature of a Newborn Black Hole from the Collapse of a Supra-massive Millisecond Magnetar

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Abstract

An X-ray plateau followed by a steep decay (“internal plateau”) has been observed in both long and short gamma-ray bursts (GRBs), implying that a millisecond magnetar operates in some GRBs. The sharp decay at the end of the plateau, marking the abrupt cessation of the magnetar’s central engine, has been considered the collapse of a supra-massive magnetar into a black hole (BH) when it spins down. If this “internal plateau” is indeed evidence of a magnetar central engine, the natural expectation in some candidates would be a signature from the newborn BH. In this work, we find that GRB 070110 is a particular case which shows a small X-ray bump following its “internal plateau.” We interpret the plateau as a spin-down supra-massive magnetar and the X-ray bump as fallback BH accretion. This indicates that a newborn BH is likely active in some GRBs. Therefore, GRB 070110-like events may provide further support to the magnetar central engine model and enable us to investigate the properties of the magnetar as well as the newborn BH.

Key words: accretion, accretion disks – black hole physics – gamma-ray burst: individual (GRB 070110)

1. Introduction

Long gamma-ray bursts (GRBs) are likely related to the core-collapse of massive stars (Woosley 1993; Paczyński 1998; MacFadyen & Woosley 1999). Short GRBs have been proposed to originate from the merger of two neutron stars (NS–NS; Eichler et al. 1989; Narayan et al. 1992) or the merger of a neutron star and a black hole (NS–BH; Paczyński 1991). However, the nature of the central engine of GRBs remains unknown.

Recently, modeling various afterglow features for both long and short GRBs within the framework of the millisecond magnetar (or pulsar with weaker magnetic field) central engine model has gained growing interest (Dai et al. 2006; Metzger et al. 2008; Dall’Ossio et al. 2011; Fan et al. 2011; Bucciantini et al. 2012; Bernardini et al. 2013; Gompertz et al. 2014; Lü & Zhang 2014; Lü et al. 2015). In particular, the so-called “internal X-ray plateaux,” with rapid decay at the end of the plateaux, are difficult to interpret within the framework of a BH central engine, but are consistent with a rapidly spinning millisecond magnetar as the central engine. The abrupt decay is naturally understood as the collapse of a supra-massive magnetar into a BH after the magnetar spins down (Troja et al. 2007; Rowlinson et al. 2010, 2013; Zhang 2014).

In fact, “internal plateaus” have been discovered in both long and short GRBs (Liang et al. 2007; Troja et al. 2007; Lyons et al. 2010; Rowlinson et al. 2010, 2013; Lü & Zhang 2014; Lü et al. 2015). If magnetars are indeed the central engines of GRBs, and the sudden drop after the plateau is interpreted as the collapse of a supra-massive NS into a BH, then signatures from this newborn BH should be expected. Especially for long GRBs, the giant X-ray bumps, likely due to fallback accretion into a BH, have been discovered e.g., in GRB 121027A and GRB 111209A (Wu et al. 2013; Yu et al. 2015; Gao et al. 2016a). These observations imply that a fraction of the envelope material would fall back and activate the accretion onto the BH at late times (Kumar et al. 2008a, 2008b). Therefore, there should be GRBs with “internal plateaus” followed by an X-ray bump.

In this paper, we find that GRB 070110 is a potential candidate of this kind. The small X-ray bump following the “internal plateau,” first uncovered by Troja et al. (2007), is likely the result of a fallback accretion. Therefore, GRB 070110 may contain a clue about the newborn BH from the collapse of a supra-massive magnetar, and provides us with a good opportunity to study the properties of this newborn BH. In Section 2, we give a general picture of the spin-down of a supra-massive magnetar and the fallback accretion onto the newborn BH. We then apply the model to GRB 070110 in Section 3. In Section 4, we briefly summarize our results and discuss the implications. Throughout the paper, a concordance cosmology with parameters = 71 km s⁻¹ Mpc⁻¹, = 0.30, and ΩΛ = 0.70 is adopted.

2. The Model

A magnetar is the proposed candidate for the central engine of some GRBs. There are several scenarios involving in this engine to explain the prompt emission: (1) the hyper-accretion onto the NS as presented in Zhang & Dai (2009, 2010) and Bernardini et al. (2013); (2) magnetic bubbles launched in a differentially millisecond proto-NS (Dai et al. 2006); (3) as suggested by Li et al. (2016), the post-merger product of NS–NS mergers might be fast-rotating supra-massive quark stars (QSs) rather than NSs, therefore the prompt emission may be powered by the phase transition of a QS (Cheng & Dai 1996); (4) a protomagnetar wind model as proposed by Metzger et al. (2011).

A supra-massive magnetar may collapse into a BH after it spins down. The observational correspondence of this prediction is the “internal X-ray plateau” discovered in some long and short GRBs (Troja et al. 2007; Lyons et al. 2010; Rowlinson...
The spin-down formula due to dipole radiation is given by Shapiro & Teukolsky (1983) as

$$P(t) = P_0 \left(1 + \frac{t}{\tau}\right)^{1/2}.$$  

A supra-massive magnetar is temporarily supported by rigid rotation, and it collapses into a BH at a later time when it spins down. The collapse occurs when the maximum gravitational mass $M_{\text{max}}$ becomes equal to the total gravitational mass of the protomagnetar $M_{\text{NS}}$. Here, the critical mass $M_{\text{max}}$ depends on the magnetar spin period $P$ (Lyndor et al. 2003) as

$$M_{\text{max}} = M_{\text{TOV}} (1 + \alpha \beta^2),$$

where $M_{\text{TOV}}$ is the maximum mass for a nonrotating NS, $\alpha$ and $\beta$ rely on the NS equation of state (EoS). Lasky et al. (2014) calculated the numerical values for $M_{\text{TOV}}$, the NS radius ($R$), the moment of inertia ($I$), and the characteristic spin-down timescale. We thus take $\tilde{\alpha}$ and $\tilde{\beta}$ as the lower limit of the spin-down timescale.

### 2.2. The X-Ray Bump due to Fallback Accretion onto the Newborn BH

The newborn BH is expected to be active. The progenitor star has a core-envelope structure, as is common in stellar models, especially in long GRBs. The core part collapses into a rapidly spinning supra-massive magnetar, and the envelope mass falls back onto the newborn BH after the collapse of the NS.

The evolution of the fallback accretion rate is described with a broken-power-law function of time (Chevalier 1989; MacFadyen et al. 2001; Zhang et al. 2008; Dai & Liu 2012) as

$$\dot{M} = \dot{M}_0 \left[\frac{1}{2} \left(\frac{t - t_0}{t_p - t_0}\right)^{-1/2} + \frac{1}{2} \left(\frac{t - t_0}{t_p - t_0}\right)^{5/3}\right]^{-1},$$

where $t_0$ is the beginning time of the fallback accretion in the core-envelope structure, and $t_p$ is the characteristic timescale.

The hyper-accreting BH system can launch a relativistic jet via neutrino-antineutrino annihilation (Popham et al. 1999; Narayan et al. 2001; Di Matteo et al. 2002; Janiuk et al. 2004, 2005, 2010; Lei et al. 2009, 2017; Xie et al. 2016). The neutrino annihilation mechanism suffers strong baryon loading from the disk and therefore may be too “dirty” to account for a GRB jet.

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**Figure 1.** Illustration of the expected “internal plateau” observations with the signature of the newborn BH. The “internal plateau” is powered by the spin-down power of a supra-massive magnetar. The steep decay marks the collapse of the magnetar into a BH when it spins down. The fallback accretion onto the BH may produce an X-ray bump at the end of the steep decay, making it a signature of the newborn BH.

**2.1. “Internal Plateau” Powered by a Spin-down Supra-massive Magnetar**

It has been suggested that “internal plateaus” are powered by a spin-down supra-massive magnetar. The characteristic spin-down luminosity $L_0$ and the characteristic spin-down timescale $\tau$ are related to the magnetar initial parameters as (Zhang & Mészáros 2001)

$$L_0 = 1.0 \times 10^{49} \text{ erg s}^{-1} (B_{p,15}^2 P_{0,-3}^{-4} R_6^6),$$

$$\tau = 2.05 \times 10^3 \text{ s} (I_{4.5} B_{p,15}^{-2} P_{0,-3}^{2} R_6^{-6}),$$

where $I_{4.5}$ is the moment of inertia in units of $10^{45} \text{ g cm}^2$, $B_{p,15}$ is the magnetic field strength in units of $10^{15} \text{ G}$, $P_{0,-3}$ is the initial period in milliseconds, and $R_6$ is stellar radius in units of $10^6 \text{ cm}$. The convention $Q = 10^6 Q_6$ is adopted in cgs units for all other parameters throughout this paper.

The spin-down luminosity $L_0$ is related to the plateau luminosity ($L_{\text{b,iso}}$) as

$$\eta_\chi L_0 = L_{\text{b,iso}} f_b,$$

where $\eta_\chi$ is the radiation efficiency, and $f_b = 1 - \cos \theta_j$ is the beaming factor.
For a Kerr BH with mass $M_\odot$ and angular momentum $J$, the BZ power (Lee et al. 2000; Li 2000; Wang et al. 2002; McKinney 2005; Lei et al. 2008, 2013; Lei & Zhang 2011) is

$$ L_{\text{BZ}} = 1.7 \times 10^{50} a_*^2 m_\odot^2 B^2_{15} F(a_*) \text{ erg s}^{-1}, \quad (7) $$

where $a_* = Jc/(GM_\odot^2)$ is the spin parameter of the BH, $B$ is the magnetic-field strength threading the BH horizon, and $F(a_*) = [(1 + q^2)/q^2][((q + 1)/q) \arctan q - 1]$, of which $q = a_*/(1 + \sqrt{1 - a_*^2})$.

Considering that the BH magnetic field is supported by the surrounding disk, one can estimate its value by equating the magnetic pressure on the horizon to the ram pressure of the accretion flow at its inner edge (Moderski et al. 1997),

$$ \frac{B^2}{8\pi} = p_{\text{ram}} \sim \rho c^2 \sim \frac{M c}{4\pi r_\text{s}^2}, \quad (8) $$

where $r = (1 + \sqrt{1 - a_*^2}) r_\text{g}$ is the radius of the BH horizon, and $r_\text{g} = GM_\odot/c^2$. Then the BZ power can be rewritten as a function of the mass accretion rate as

$$ L_{\text{BZ}} = 9.3 \times 10^{53 \theta} \frac{a_\star^2 m \dot{M}}{(1 + \sqrt{1 - a_*^2})^2} \text{ erg s}^{-1}, \quad (9) $$

where $\dot{m} \equiv \dot{M}/(M_\odot \text{ s}^{-1})$ is the dimensionless accretion rate.

The observed X-ray luminosity is connected to the BZ power via the X-ray radiation efficiency $\eta$ and the jet beaming factor $f_\phi$, i.e.,

$$ \eta_{\text{X}} L_{\text{BZ}} = f_\phi L_{\text{X,iso}}, \quad (10) $$

where $\eta_{\text{X}}$ and $f_\phi$ use the same values as in Section 2.1.

The BH would be spun-up by accretion while spun-down by the BZ mechanism. The evolution equations are given by Wang et al. (2002),

$$ \frac{dM c^2}{dt} = M c^2 E_{\text{ms}} - L_{\text{BZ}}, \quad (11) $$

$$ \frac{da_*}{dt} = \frac{(M_\text{ms} - \tau_{\text{BZ}}) c}{GM_\odot^2} - \frac{2a_* (M c^2 E_{\text{ms}} - L_{\text{BZ}})}{M c^2}, \quad (12) $$

where $\tau_{\text{BZ}}$ is the BZ torque with expression,

$$ \tau_{\text{BZ}} = 3.36 \times 10^{45} a_\star^2 q^{-1} m_\odot^2 B^2_{15} F(a_*) \text{ g cm}^2 \text{ s}^{-2}. \quad (13) $$

In Equations (11) and (12), $E_{\text{ms}}$ and $l_{\text{ms}}$ are the specific energy and angular momentum at the radius of the innermost stable circular orbit $r_{\text{ms}}$ of the disk, respectively, which are defined (Novikov & Thorne 1973) as

$$ l_{\text{ms}} = \frac{GM_\odot}{c} \frac{2(3\sqrt{R_{\text{ms}}} - 2a_*)}{\sqrt{3} \sqrt{R_{\text{ms}}}}, \quad (14) $$

$$ E_{\text{ms}} = \frac{4\sqrt{R_{\text{ms}}} - 3a_*}{\sqrt{3} \sqrt{R_{\text{ms}}}}, \quad (15) $$

where $R_{\text{ms}} = r_{\text{ms}}/r_\text{g} = 3 + Z_2 - ((3 - Z_1)(3 + Z_1 + 2Z_2))^{1/2}$, for $0 \leq a_* \leq 1$ (Bardeen et al. 1972), where $Z_1 \equiv 1 + (1 - a_*^2)^{1/3} [(1 + a_*^2)^{1/3} + (1 - a_*^2)^{1/3}]$, and $Z_2 \equiv (3a_*^2 + Z_1^2)^{1/2}$.

Figure 2. Modeling results for the X-Ray Telescope (XRT) and optical light curve of GRB 070110. The observed data are exhibited with black (XRT, using the data from the Swift data archive) and magenta (optical U-band, the data were taken from Troja et al. 2007) points with error bar, and the theoretical modeling is shown with red (“internal plateau” phase) and blue (X-ray bump phase) solid lines. The thin black and magenta dotted lines denote the external shock component in the X-ray and optical band, respectively. The blue dashed line corresponds to the contribution from the BZ jet according to the fallback BH disk.

3. GRB 070110

GRB 070110, with duration $T_\text{90}(15-150 \text{ keV}) = 89 \pm 7 \text{ s}$ and redshift $z = 2.352 \pm 0.001$, was triggered by the Swift Burst Alert Telescope (BAT) on 2007 January 10 (Troja et al. 2007). The fluence over the 15–150 keV band was $1.8^{+0.3}_{-0.2} \times 10^{-6} \text{ erg cm}^{-2}$, from which one can derive an observed isotropic energy of $E_{\gamma,\text{iso}} \approx 3.1 \times 10^{52} \text{ erg}$ (Troja et al. 2007; Du et al. 2016).

The afterglow of GRB 070110 (Troja et al. 2007) showed a near-flat plateau ($\alpha \sim 0.05$) with a flux $L_{\text{b,iso}} \sim 10^{46} \text{ erg s}^{-1}$ in 0.3–10 keV. It extends to over $10^4 \text{ s}$ before rapidly falling off with a decay index $\alpha \sim 9$ (see the red dashed line in Figure 2). Such a rapid decay cannot be accommodated in any external shock model, so the entire X-ray plateau emission has to be attributed to the internal dissipation of a central engine wind (Lü & Zhang 2014; Du et al. 2016).

After the sharp decay following the plateau, a small bump was observed (Troja et al. 2007). In Troja et al. (2007), the fast rise of GRB 070110, after the abrupt drop at $t_\text{f} \approx 1.4 \times 10^4 \text{ s}$, and the following decay is well described by a fast-rise-exponential-decay (FRED) profile, peaking at $t_\text{F}(1 + z) \approx 5 \times 10^3 \text{ s}$. The late X-ray ($t_\text{F} = 10^5 \text{ s}$) exhibited a power-law decay with $\alpha \sim 0.7$, which can be interpreted as the standard external forward shock afterglow. To exhibit the significance of the bump, we perform an empirical function fit to the late-time ($t \geq 1.4 \times 10^4 \text{ s}$) X-ray light curve with two distinct models, a single power-law (SPL) function and an FRED bump+power-law (PL) function. Our results show that the fit with the FRED+PL model is significantly better than the one with the SPL model (the reduced chi-square ($\chi^2$-values) are $2.7 (0.00021)$ for the FRED+PL model, and 10.03 (0.18152) for the SPL model). Considering that the FRED+PL model will introduce extra parameters compared to the PL model, we adopt a Bayesian information criterion (BIC) to evaluate the goodness of the two models (Schwarz 1978). The BIC can be written as $\text{BIC} = n \log(\text{RSS}/n) + k \log(n)$, where $k$ is the number of free parameters, $n$ is the number of data points, and RSS is the residual sum of squares. As suggested by Schwarz (1978), the model with the lowest BIC is preferred. We find that
the BIC values are $-77.48$ for the FRED+PL model, and $-72.71$ for the SPL model. Therefore, from a statistical point of view, modeling with a FRED-like bump is more consistent with the data.

The optical afterglow was detected by Swift/Ultraviolet and Optical Telescope (UVOT) in the white, U, B, and V filters. The UVOT light curves show a decaying behavior that can be well described by a simple power law. It was found that the UVOT late slopes ($\alpha_{\text{sp}} \sim 0.63$) are consistent, within the errors, with the late-time X-ray slope. The late optical/X-ray spectrum ($t = 100$ ks) can be described by a continuous power law (with spectral index $\beta = 1.00 \pm 0.14$), indicating that the optical and late X-ray afterglow may arise from the same physical component.

In Figure 2, the X-ray and optical light curve of GRB 070110 are presented with black and magenta points, respectively. An “internal X-ray plateau” and a small X-ray bump are identified, making GRB 070110 a possible candidate with which to study the magnetar and the newborn BH.

Now we apply our model to GRB 070110. The X-ray plateau can be interpreted with the magnetar model using Equations (1)-(3). Since no jet break feature was observed, Du et al. (2016) estimated a lower limit of the jet opening angle $\theta_j$ with the last observed point ($t_j = 25$ days) in the X-ray afterglow, i.e., $\theta_j > 7^2$. In our calculation, $\theta_j \approx 10^2$ (and thus $f_0 \approx 0.02$) is taken. In fact, the modeling results for the afterglow component depend weakly on the values of $\theta_j$.

We adopt a numerical code developed for the external shock model (Gao et al. 2013; Wang et al. 2014) to model both the late-time ($>10^5$ s) X-ray afterglow and the U-band optical light curves, as shown with gray (X-ray) and magenta (optical) dotted lines in Figure 2. The empirical function fitting to the optical light curve by Troja et al. (2007) suggests a peak at 1000 s, which is usually taken as the jet deceleration time $t_{\text{dec}}$. Since $t_{\text{dec}} \propto E_{k,\text{iso}}^{1/3} n^{-1/3} t_0^{-2/3}$, the values of jet isotropic kinetic energy $E_{k,\text{iso}}$, ambient medium density $n$, and initial bulk Lorentz factor $\Gamma_0$ are chosen to satisfy $t_{\text{dec}} \sim 1000$ s. The optical to X-ray spectral index $\beta = 1.00 \pm 0.14$ suggests an electron energy spectral index of $\nu \sim 2$. Other microphysics shock parameters, such as $\epsilon_{\text{el}}$ and $\epsilon_{\text{b}}$, are taken as values so that the model can fit both the X-ray and optical flux. However, these model parameters still suffer degeneracy when fitting the X-ray and optical data (Kumar & Zhang 2015). For the purpose of this work, we do not attempt to fit the data across a large parameter space. In Table 1, we present a set of afterglow parameter values that interpret the data well.

The radiation efficiency $\eta_X$ is unknown due to the lack of knowledge about the jet dissipation process during plateau and X-ray bump phases. In our calculations, we take $\eta_X \sim 0.1$ as a typical value.

Assuming the spin-down timescale $\tau \sim t_0/(1 + z)$ and adopting EoS GM1, one can infer a magnetar initial period of $P_0 \sim 8.2$ ms and a magnetic field $B_{0,\text{iso}} \sim 4.95 \times 10^{15}$ G from the data, as shown in Table 1. The mass of the supra-massive magnetar is $M_{\text{NS}} \sim 2.37 M_\odot$, which equals the critical mass $M_{\text{max}}$ at collapse time $t_{\text{c}}$. The predicted spin-down luminosity of the magnetar is also shown with a red solid line in Figure 2. The red dashed line in Figure 2 is drawn directly with the empirical function $L_{X,\text{iso}} = L_{b,\text{iso}}(t_0/t_0)^{3/2}$.

The FRED-shaped X-ray bump in GRB 070110, implying the restart of the central engine after the sudden drop of the “internal plateau,” is not predicted in the previous supra-massive magnetar model.

Bumps in the GRB afterglow are often interpreted as being due to density variations in the circumburst medium (Dai & Lu 2002, Dai & Wu 2003). However, this model predicts a very smooth light curve, as shown in Dai & Wu (2003) and Uhm & Zhang (2014), which is inconsistent with the fast-rise-shaped bump in GRB 070110. After the collapse of the supra-massive magnetar, the magnetic flux will be ejected based on the no-hair theorem of BH, which leads to a short duration flare activity (in the radio band, it might be a fast radio burst) just at the end of the plateau (Zhang 2014). These features are quite different than those in GRB 070100. Furthermore, the total magnetic energy in this model is small compared to the GRB energy, so it would have no significant imprint in the X-ray light curve. In this paper, we attribute it to the fallback accretion onto the newborn BH.

The initial setup for the BH can be obtained by assuming that the newborn BH inherits the mass and angular momentum from the supra-massive magnetar. With the above parameters for a magnetar, we get an initial BH mass $M_{\text{BH}} \sim 2.37 M_\odot$, and initial spin $a \approx 0.04$ (by using $J = 2\pi I/P_0$). Then we calculate the time evolution of the BZ power, and compare it to the observations of the X-ray bump. We use the same radiation efficiency $\eta_X$ and beaming factor $f_0$ as those for the plateau. The calculation starts at $t_0 = 4.8 \times 10^4/(1 + z)$ s.

The modeling of the X-ray bump is exhibited in Figure 2 (blue dashed line). The blue solid line denotes the total emission by including the contributions from both the BZ jet (blue dashed line) and the external shock (gray dotted line). The modeling parameters are summarized in Table 1.
The peak accretion rate is $M_\text{acc} \sim 1.0 \times 10^{-5} M_\odot$. The total accreted mass should be $M_\text{acc} \sim 0.085 M_\odot$. During the accretion, the BH mass increases from $2.37 M_\odot$ to $2.45 M_\odot$, and the spin from 0.04 to 0.15.

The X-ray bump appears at $\sim 48,000$ s after the GRB trigger, which, divided by $1+z$, corresponds to $t_\text{BH} \sim t_0 \sim 1.4 \times 10^4$ s. This suggests that the minimum radius around which matter starts to fall back is $r_\text{BH} \sim 3.7 \times 10^{11}(M_i/2.5 M_\odot)^{1/3}(t_\text{BH}/14,000$ s)$^{2/3}$ cm, which is consistent with the typical radius of a Wolf–Rayet star.

4. Conclusion and Discussion

"Internal plateaus" in GRB afterglows are commonly interpreted in association with a supra-massive magnetar (Troja et al. 2007; Lyons et al. 2010; Lü & Zhang 2014; Lü et al. 2015; Gao et al. 2016b). The sudden steep decay implies the collapse of a supra-massive magnetar into a BH. To check this model, we expect a signature of the newborn BH from the observation.

GRB 070110, a long burst ($T_{90} \sim 90$ s), is a typical example with an "internal plateau" (Troja et al. 2007). Interestingly, a small X-ray bump emerges at the end of the rapid decay of this internal plateau, suggesting the reactivation of a central engine after the collapse of supra-massive NS. Such a bump is beyond the prediction of the magnetar central engine model, but can be well interpreted with the fallback accretion into a BH. Our work implies that some GRBs are still active after the collapse of the magnetar, showing possible signatures of the newborn BH.

GRB 070110 is not the only burst showing such activity. As shown in Figure 3, GRB 110731A, a "rest-frame short" GRB detected by Fermi and Swift observatories at redshift of $z = 2.83$ (Tanvir et al. 2011), may serve as another example. From the combination of BAT and XRT data, an internal plateau is identified with break time $t_b \sim 6$ s. At the end of the steep decay, a fast rise appeared at $\sim 30$ s. Considering the short period of the plateau, GRB 110731A may represent a different evolutionary path of the magnetar. The progenitor of GRB 110731A is probably a compact-star merger (Lü et al. 2017).

Initially, the newborn supra-massive NS would be differentially rotating. Within a timescale of seconds, the combination of magnetic breaking and viscosity would drive the star to the uniform rotation phase. The interpretation with our model indicates that the magnetar would have a period of $P_0 \sim 1.3$ ms and a magnetic field of $B_0 \sim 5.0 \times 10^{16}$. If the initial spin period in this rigid-rotation phase is larger than the critical period supporting the supra-massive NS by centrifugal force, the magnetar would promptly collapse into a BH with initial mass $M_i \sim 2.37 M_\odot$ and initial spin $a_i \sim 0.2$. Some of the surrounding matter initially blocked by the magnetic barrier of the magnetar would begin to fall back and be accreted by the newborn BH, which in turn produces the observed X-ray bump at $t \sim 30$ s. The accreted mass should be $\sim 0.002 M_\odot$ based on our model. Considering that the typical mass of the ejecta during a merger is in the range $10^{-4} - 10^{-2} M_\odot$ (Hotokezaka et al. 2013), we would expect a few percent of them to be accreted by the newborn BH.

If magnetars are the central engines of some GRBs, then several evolutionary results of magnetars are expected: (1) the immediate collapse into a BH; (2) the collapse of a supra-massive magnetar into a BH after it spins down; and (3) a stable magnetar (Lü & Zhang 2014; Lü et al. 2015; Gao et al. 2016b). Our analysis suggests that some magnetars may indeed collapse into a BH, which provides direct support for the magnetar central engine model.

However, most GRBs with "internal plateaus" do not show clear BH signatures. The fallback processes would be intrinsically weak, especially at late time. The bounding shock responsible for the associated supernova or central engine is larger, which might be in the majority of cases, the fallback process disappears.

For simplicity, we did not include the rotational energy loss of the supra-massive magnetar due to gravitational wave (GW) emission. As discussed in Fan et al. (2013), Zhang (2013), Lü et al. (2015), and Gao et al. (2016b), significant energy may be released in the form of GWs. We will investigate this in detail in the future.

In this paper, we adopt neutron star EoS GM1 in the modeling. Recently, (Li et al. 2016) suggested that the "internal plateau" might be produced by a QS. Our model is not sensitive to the EoS, therefore our main results will still hold even if we adopt QS EoSs.

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