The electromagnetic and gravitational-wave radiations of X-ray transient CDF-S XT2

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Abstract Binary neutron star (NS) mergers may result in remnants of supra-massive or even stable NS, which have been supported indirectly by observed X-ray plateau of some gamma-ray bursts (GRBs) afterglow. Recently, Xue et al. (2019) discovered a X-ray transient CDF-S XT2 that is powered by a magnetar from merger of double NS via X-ray plateau and following stepper phase. However, the decay slope after the plateau emission is a little bit larger than the theoretical value of spin-down in electromagnetic (EM) dominated by losing its rotation energy. In this paper, we assume that the feature of X-ray emission is caused by a supra-massive magnetar central engine for surviving thousands of seconds to collapse black hole. Within this scenario, we present the comparisons of the X-ray plateau luminosity, break time, and the parameters of magnetar between CDF-S XT2 and other short GRBs with internal plateau samples. By adopting the collapse time to constrain the equation of state (EOS), we find that three EOSs (GM1, DD2, and DDME2) are consistent with the observational data. On the other hand, if the most released rotation energy of magnetar is dominated by GW radiation, we also constrain the upper limit of ellipticity of NS for given EOS, and it is range in $[0.32-1.3] \times 10^{-3}$. Its GW signal can not be detected by aLIGO or even for more sensitive Einstein Telescope in the future.

Key words: stars: magnetars

1 INTRODUCTION

The merger of a binary neutron star (NS) system is thought to be potential sources of producing both gravitational wave (GW) and associated electromagnetic (EM) signals (Berger 2014 for review). One solid
is already detected by Advanced LIGO, VIRGO, and other telescopes (Abbott et al. 2017; Goldstein et al. 2017; Coulter et al. 2017; Zhang et al. 2018). However, the remnants of double NS merger remain an open question.

From the theoretical point of view, there are four different types of merger remnants that are dependent on the total mass of the system and the poorly known NS equation of state (EOS; Rosswog et al. 2000; Dai et al. 2006; Fan & Xu 2006; Metzger et al. 2010; Rezzolla et al. 2011; Giacomazzo & Perna 2013; Zhang 2013; Lasky et al. 2014; Li et al. 2016). (1) a promptly formed BH (Hotokezaka et al. 2011); (2) a hyper-massive NS, can be survived for $\sim 100$ ms before collapsing into a BH (Baumgarte et al. 2000; Shibata & Taniguchi 2006; Palenzuela et al. 2015); (3) a supra-massive NS, is supported by rigid rotation and survives for seconds to hours (Dai et al. 2006; Rowlinson et al. 2010; Hotokezaka et al. 2013; Zhang 2014; Lü et al. 2015; Gao et al. 2016; Kiuchi et al. 2018); (4) a stable NS (Dai & Lu 1998; Zhang & Mészáros 2001; Yu et al. 2010; Metzger et al. 2011; Bucciantini et al. 2012; Lü & Zhang 2014).

Recently, Xue et al. (2019) discovered a X-ray transient CDF-S XT2 that is associated with a galaxy at redshift $z = 0.738$, and its X-ray light curve is consistent with magnetar central engine model which is originated from double neutron star merger. The magnetar parameters are inferred by invoking the its X-ray plateau and followed decay segment in their work, and found that they are consistent with the parameters of magnetar in typical short GRBs. However, the decay slope after the plateau emission is a little bit larger than the theoretical value of magnetar spin-down. On the other hand, a lower efficiency ($\eta = 0.001$) is adopted to estimate the parameters of magnetar for this transient in Xue et al. (2019). Here, we assume that the feature of X-ray emission is caused by a supra-massive magnetar central engine for surviving thousands of seconds to collapse black hole. Within this scenario, most rotation energy of magnetar may be dissipated in two ways. One is that the most of rotation energy is transformed into kinetic energy with injecting pulsar wind (Xiao & Dai 2019). The other possibility is that most of the rotational energy was carried away via the strong gravitational wave radiation (Fan et al. 2013; Lasky & Glampedakis 2016; Lü et al. 2018). In this paper, by considering two scenarios of rotation energy loss of magnetar for post-merger (i.e., EM dominated or GW dominated), we infer the surface magnetic field and initial period of NS, and constrain the EOS and ellipticity of NS, as well as detection probability of GW.

This paper is organized as follows. The empirical fitting of X-ray light curve for transient CDF-S XT2 is presented in section 2. Some comparisons between CDF-S XT2 and other short GRBs with internal plateau, as well as EOS are shown in section 3. In section 4, we constrain the ellipticity of NS, and calculate the detection probability of GW. The conclusions, along with some discussions, are presented in Section 5. Throughout this paper, a concordance cosmology with parameters $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.30$, and $\Omega_\Lambda = 0.70$ is adopted.

## 2 LIGHT CURVE FIT AND CENTRAL ENGINE OF CDF-S XT2

### 2.1 Light curve fit of CDF-S XT2

The X-ray data of CDF-S XT2 observed by Chandra within energy band 0.3-10 keV are taken from Xue et
expression as

\[ L = L_0 \left[ \left( \frac{t}{t_b} \right)^{\omega \alpha_1} + \left( \frac{t}{t_b} \right)^{\omega \alpha_2} \right]^{-1/\omega} \]  

(1)

where \( t_b(2525 \pm 242) \) s is the break time, \( L_b = L_0 \cdot 2^{-1/\omega} = (1.28 \pm 0.16) \times 10^{45} \text{ erg s}^{-1} \) is the luminosity at the break time \( t_b \), \( \alpha_1 = (0.09 \pm 0.11) \) and \( \alpha_2 = (2.43 \pm 0.19) \) are decay indices before and after the break, respectively. The \( \omega \) describes the sharpness of the break. The larger the \( \omega \) parameter, the sharper the break, and \( \omega = 3 \) is fixed for the light curve fitting. An IDL routine named “mpfitfun.pro” is employed for our fitting (Markwardt 2009). This routine performs a Levenberg-Marquardt least-square fit to the data for a given model to optimize the model parameters. The light curve fit is shown in Figure 1.

2.2 Central engine of CDF-S XT2

X-ray transient CDF-S XT2 associated with a galaxy at redshift \( z = 0.738 \), lies in the outskirts of its star-forming host galaxy with a moderate offset from the galaxy center, and no significant source-like gamma-ray emission signal above background. Those observed properties are similar with other typical short GRBs, but in off-axis observed (Xue et al. 2019). On the other hand, the estimated event rate density of this event is similar with double NS merger rate density inferred from the detection of GW170817, suggesting that the progenitor of this event is likely from double NS merger (Xue et al. 2019). Moreover, the observed X-ray plateau of CDF-S XT2 is consistent with wind dissipation of magnetar central engine, and it indicate that the remnants of such double NS merger should be either supra-massive NS or stable NS. However, the decay slope after the plateau emission \( (t^{-2.43}) \) is a little bit larger than the theoretical value of spin-down \( (t^{-2}) \) in electromagnetic (EM) dominated by losing its rotation energy. Here, we assume that the feature of X-ray emission is caused by a supra-massive magnetar central engine for surviving thousands of seconds to collapse black hole.

In order to compare the properties of CDF-S XT2 with other short GRBs with internal plateau, Fig. 2 shows the correlation between break luminosity \( (L_b) \) and collapse time \( (\tau_{\text{col}} = t_b/(1 + z)) \), as well as the distributions of \( L_b \) and \( \tau_{\text{col}} \). We find that the CDF-S XT2 fall into the 2σ deviation in \( L_b - \tau_{\text{col}} \) diagram, suggesting that the other short GRBs with internal plateau samples shared similar central engine with the CDF-S XT2. However, the distributions of luminosity and collapse time of the CDF-S XT2 is much lower and longer than other short GRBs with internal plateau samples, respectively. It may be caused by the directions of observations (i.e., on and off-axis with short GRBs and the CDF-S XT2), or having different populations of magnetar.

If we believe a supramassive NS as a potential candidate central engine of CDF-S XT2. One interesting question is that what is the energy loss channel of the rotating magnetar, dominated by magnetic dipole or GW radiation. We will discuss more details for the rotation energy loss of magnetar dominated by EM or
3 THE ROTATION ENERGY LOSS OF MAGNETAR VIA EM EMISSION

3.1 The derived parameters of magnetar

The energy reservoir of a millisecond magnetar is the total rotation energy, which reads as

$$E_{\text{rot}} = \frac{1}{2} I \Omega^2 \simeq 2 \times 10^{52} \text{ erg } M_{1.4} R_6^2 P_{-3}^{-2},$$

(2)

where $I$ is the moment of inertia, $\Omega$, $P$, $R$, and $M$ are the angular frequency, rotating period, radius, and mass of the neutron star, respectively. The convention $Q = 10^7 Q_x$ in cgs units is adopted. A magnetar spinning down loses its rotational energy via both magnetic dipole torques ($L_{\text{EM}}$) and GW ($L_{\text{GW}}$) radiations (Zhang & Mészáros 2001; Fan et al. 2013; Giacomazzo & Perna 2013; Lasky & Glampedakis 2016; Lü et al. 2018),

$$-\frac{dE_{\text{rot}}}{dt} = -I \Omega \dot{\Omega} = L_{\text{total}} = L_{\text{EM}} + L_{\text{GW}} = \frac{B_p^2 R_6^6 \Omega^4}{6c^3} + \frac{32G I^2 \epsilon^2 \Omega^6}{5c^5},$$

(3)

where $B_p$ is the surface magnetic field at the pole and $\epsilon = 2(I_{xx} - I_{yy})/(I_{xx} + I_{yy})$ is the ellipticity describing how large the neutron star deformation. $\dot{\Omega}$ is the time derivative of the angular frequency. One can find that for a magnetar with given $R$ and $I$, its $L_{\text{EM}}$ depends on $B_p$ and $\Omega$, and $L_{\text{GW}}$ depends on $\epsilon$ and $\Omega$.

If the rotation energy loss of magnetar is dominated by EM emission, one has

$$L_{\text{EM}} \simeq -I \Omega \dot{\Omega} = \frac{\eta B_p^2 R_6^6 \Omega^4}{6c^3},$$

(4)

where $\eta$ is the efficiency of converting the magnetar wind energy into X-ray radiation. The characteristic spin-down luminosity ($L_{\text{EM,sd}}$) and time scale ($\tau_{\text{EM,sd}}$) of magnetar can be given as,

$$L_{\text{EM,sd}} = \frac{\eta B_p^2 R_6^6 \Omega_0^4}{6c^3} \simeq 1.0 \times 10^{46} \text{ erg s}^{-1} (\eta - 3 B_p^2 P_{0,-3}^{-4} R_6^6),$$

(5)

$$\tau_{\text{EM,sd}} = \frac{3c^3 I}{B_p^2 R_6^6 \Omega_0^2} \simeq 2.05 \times 10^3 \text{ s } (I_{45} B_{p,15}^2 P_{0,-3}^2 R_6^{-6}),$$

(6)

where $\Omega_0$ and $P_0$ are initial angular frequency and period at $t = 0$, respectively.

Within the magnetar central engine scenario, the observed plateau luminosity is closed to $L_{d}$, which is roughly equal to $L_{\text{EM,sd}}$, and $\tau_{\text{EM,sd}} > \tau_{\text{col}}$. One can derive the magnetar parameters $B_p$ and $P_0$,

$$B_{p,15} = 2.05 (\eta - 3 I_{45} R_6^{-3} L_{\text{EM,sd,46,5 EM,sd,3}}^{-1/2} L_{\text{EM,sd,46,5 EM,sd,3}}^{-1/2}) \text{ G},$$

(7)

$$P_{0, -3} = 1.42 (\eta - 3 I_{45} L_{\text{EM,sd,46,5 EM,sd,3}}^{-1/2} L_{\text{EM,sd,46,5 EM,sd,3}}^{-1/2}) \text{ s}.$$

(8)

As radiation efficiency $\eta$ depends strongly on the injected luminosity and wind saturation Lorentz factor (Xiao& Dai 2019). By adopting the lower limit of $\tau_{\text{EM,sd}}$, we derive the upper limits of $P_0$ and $B_p$ with

$$L_{\text{obs}} \simeq 10^{36} \text{ erg s}^{-1}.$$
and $B_p < 1.2 \times 10^{16} \text{ G}$ for $\eta = 0.01$, and $P_0 < 33.8 \times 10^{-3} \text{ s}$ and $B_p < 4 \times 10^{16} \text{ G}$ for $\eta = 0.1$. Figure 3 shows the $B_p - P_0$ diagram for X-ray transient CDF-S XT2 with different $\eta$ values, and compares with other short GRBs with internal plateau sample taken from Lü et al. (2015). It seems that small $P_0$ required by supra-massive magnetar is needed lower radiation efficiency, and estimated $B_p$ of CDF-S XT2 is lower than other typical short GRBs samples for smaller $P_0$. It may be either off-axis observations or different population of CDF-S XT2 by comparing with short GRBs.

### 3.2 Equation of state of NS

The inferred collapsing time can be used to constrain the neutron star EOS (Lasky et al. 2014; Ravi & Lasky 2014; Lü et al. 2015). The basic formalism is as follows.

The standard dipole spin-down formula gives (Shapiro & Teukolsky 1983)

$$P(t) = P_0(1 + \frac{4\pi^2 B_p^2 R^6}{3c^3 I P_0^2} t^{1/2})$$

$$= P_0(1 + \frac{t}{\tau_{\text{EM,sd}}})^{1/2}.$$  \hspace{1cm} (9)

The maximum NS mass for a non-rotating NS ($M_{\text{TOV}}$) can be derived for given EOS of NS. The maximum gravitational mass ($M_{\text{max}}$) depends on spin period, read as (Lyford et al. 2003)

$$M_{\text{max}} = M_{\text{TOV}}(1 + \hat{\alpha} P^\beta)$$ \hspace{1cm} (10)

where $\hat{\alpha}$, $\hat{\beta}$, and $M_{\text{TOV}}$ depend on the EOS of NS.

As the neutron star spins down, the centrifugal force can no longer sustain the star, and the NS will collapse into a black hole. By using Equation (9) and (10), one can derive the collapse time as function of $M_p$,

$$t_{\text{col}} = \frac{3c^3 I}{4\pi^2 B_p^2 R^6} \left[\left(\frac{M_p - M_{\text{TOV}}}{\hat{\alpha} M_{\text{TOV}}}\right)^{2/\beta} - P_0^2\right]$$

$$= \frac{\tau_{\text{EM,sd}}}{P_0^2} \left(\frac{M_p - M_{\text{TOV}}}{\hat{\alpha} M_{\text{TOV}}}\right)^{2/\beta} - P_0^2].$$ \hspace{1cm} (11)

Here, we consider 12 EOS that are reported in the literatures (Lasky et al. 2014; Ravi & Lasky 2014; Li et al. 2016; Ai et al. 2018). The basic parameters of those EOS are shown in Table 1.

As noted, one can infer $B_p$, $P_0$, and $t_{\text{col}}$ from the observations by adopting $\eta = 0.001$. Following the method of Lasky et al. (2014), a tight mass distribution of the our Galactic binary NS population is adopted (e.g., Valentim et al. 2011; Kiziltan et al. 2013), and one can infer the expected distribution of protomagnetar masses, which is found to be $M_p = 2.40^{+0.13}_{-0.15} M_{\odot}$. For X-ray transient CDF-S XT2, the lower limit of $\tau_{\text{EM,sd}} = t_{\text{col}}$ is derived. Figure 4 presents the collapse time ($t_{\text{col}}$) as a function of protomagnetar mass ($M_p$) for CDF-S XT2 with different EOS. Our results show that the GM1, DD2, and DDME2 models give an $M_p$ band falling within the $2\sigma$ region of the protomagnetar mass distribution, so that the correct EOS should be close to those three models. The maximum mass for non-rotating NS in those three models are $M_{\text{TOV}} = 2.37 M_{\odot}$, $2.42 M_{\odot}$, and $2.48 M_{\odot}$, respectively.

### 4 THE ROTATION ENERGY LOSS OF MAGNETAR VIA GW RADIATION

A survived supra-massive NS central engine requires a more fast spinning ($P_0 \sim 1 \text{ ms}$) to support the
Glampedakis 2016). As mentioned above, the estimated periods of magnetar are considerably longer ($\eta = 0.01$ and 0.1) than that expected in the double neutron star merger model. It seems that $\eta$ should be as low as 0.001 or even smaller to obtain the lower period of magnetar. If this is the case, the rotation energy loss of magnetar is either transformed to kinetic energy of outflow or dominated by GW radiation (Lan et al. 2020). Xiao & Dai (2019) present a more details for the first situation. In this section, we focus on considering the most rotation energy of magnetar dissipated via GW radiation.

4.1 Constraining the ellipticity of NS

Within GW dominated scenario, one has (Lü et al. 2018),

$$L_{GW} \simeq -I\Omega \dot{\Omega} = \frac{32GI^2\epsilon^2\Omega_0^6}{5c^5}. \quad (12)$$

The characteristic spin-down luminosity ($L_{GW,\text{sd}}$) and time scale ($\tau_{GW,\text{sd}}$) of NS can be given as,

$$L_{GW,\text{sd}} = \frac{32GI^2\epsilon^2\Omega_0^6}{5c^5}$$
$$\simeq 1.08 \times 10^{48} \text{ erg s}^{-1}(I_{45}^2\epsilon_{-3}^2 P_{0,-3}^{-6}), \quad (13)$$

$$\tau_{GW,\text{sd}} = \frac{5c^5}{128GI\epsilon_4\Omega_0^4}$$
$$\simeq 9.1 \times 10^3 \text{ s } (I_{45}^{-1}\epsilon_{-3}^2 P_{0,-3}^4). \quad (14)$$

The supra-massive NS of CDF-S XT2 has collapse into black hole before it is spin-down, so that one has $\tau_{GW,\text{sd}} > \tau_{\text{col}}$. Combining with Equation (14), the upper limit of ellipticity ($\epsilon$) can be expressed as

$$\epsilon < 2.5 \times 10^{-3} I_{45}^{1/2} P_{0,-3}^2. \quad (15)$$

The maximum value of $\epsilon$ for different EOS with $P_0 = 1 \text{ ms}$ are shown in Table 1. We find that those values are in the range of $[0.32 - 1.3] \times 10^{-3}$. This upper limit value is larger than the maximum elastic quadrupole deformation of conventional neutron stars, but is comparable to the upper limit derived for crystalline colour-superconducting quark matter (Lin 2007; Johnson-McDaniel & Owen 2014).

4.2 Detection Probability of a GW

If most of the rotation energy is released via GW radiation with a frequency $f$, the GW strain for a rotating neutron star at distance $D_L$ can be expressed as,

$$h(t) = \frac{4GI\epsilon}{D_Lc^4}\Omega(t)^2. \quad (16)$$

The signal-to-noise ratio of optimal matched filter can be expressed as

$$\rho^2 = \int_{f_1}^{f_2} \frac{\hat{h}^2(f)}{S_h(f)} df \quad (17)$$

where $f_1$ and $f_2$ are the initial and final GW frequencies, respectively. $\hat{h}(f)$ is the Fourier transform of $h(t)$. The noise power spectral density of the detector (Lasky &
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Glampedakis 2016). The characteristic amplitude of GW from a rotating NS can be estimated as (Corsi & Mészáros 2009; Hild et al. 2011; Lasky & Glampedakis 2016; Lü et al. 2017),

$$h_c = f h(t) \sqrt{\frac{dt}{df}} = \frac{f}{D_L} \sqrt{\frac{5GI}{2c^3f}}$$

$$\approx 8.22 \times 10^{-24} \left( \frac{f}{10^{45} \text{ g cm}^2 \text{ s}^{-1}} \frac{f}{1 \text{ kHz}} \right)^{1/2} \left( \frac{D_L}{100 \text{ Mpc}} \right)^{-1}. \tag{18}$$

For X-ray transient CDF-S XT2, its redshift $z = 0.738$ corresponds to $D_L \approx 4480 \text{ Mpc}$. By adopting the frequency range of GW from $f = 120 \text{ Hz}$ to $1000 \text{ Hz}$, one can estimate the maximum value of the strain $h_c$ for different EOS of NS. The estimated values of $h_c$ are reported in Table 1. The maximum value of the strain $h_c$ for NL3ωρ is about $5 \times 10^{-25}$, which is about one order of magnitude smaller than the advanced-LIGO sensitivity, and also less than more sensitive Einstein Telescope (ET; see Figure 5). It means that even if the merger remnant of double NS of this transient is a millisecond massive NS, the post merger GW signal is undetectable when the rotation energy of the NS is taken away by the GW radiation.

5 CONCLUSIONS AND DISCUSSION

The X-ray transient CDF-S XT2 associated with a galaxy at redshift $z = 0.738$, lies in the outskirts of its star-forming host galaxy with a moderate offset from the galaxy center, and no significant source-like gamma-ray emission signal above background (Xue et al. 2019). Moreover, the estimated event rate density of this event is similar with double NS merger rate density inferred from the detection of GW170817, and the observed X-ray plateau is consistent with wind dissipation of magnetar central engine. Those observed evidences support that the progenitor of this event is likely from double NS merger, and the remnants of such double NS merger should be either supra-massive NS or stable NS. Moreover, Xiao et al (2019) proposed that both the light curve and spectral evolution of CDF-S XT2 can be well explained by the internal gradual magnetic dissipation process in an ultra-relativistic wind. Sun et al. (2109) also presented that this transient is only observed from different zone, defined as free zone where the X-ray emission from magnetar spin-down can escape freely. Alternatively, Peng et al. (2019) argued that this transient is possible from tidal disruption event.

The decay slope after the plateau emission of CDF-S XT2 ($t^{-2.43}$) is a little bit larger than the theoretical value of spin-down ($t^{-2}$) in electromagnetic (EM) dominated by losing its rotation energy. In this work, we assume that the feature of X-ray emission is caused by a supra-massive magnetar central engine for surviving thousands of seconds to collapse black hole. Within this scenario, in order to compare the observed properties of X-ray emission between CDF-S XT2 and other short GRBs with internal plateau, we show the correlation between break luminosity and collapse time, as well as the distributions of them. We find that the CDF-S XT2 fall into the $2\sigma$ deviation in $L_b - \tau_{col}$ diagram, suggesting that the other short GRBs with internal plateau samples shared similar central engine with the CDF-S XT2. However, the distributions of luminosity and collapse time of the CDF-S XT2 is much lower and longer than other short GRBs with internal plateau samples, respectively. It may be caused by the directions of observations (i.e., on- and
On the other hand, one consider two channels of rotation energy loss of supra-massive magnetar, one is EM dominated, and the other is GW dominated. Within the first scenario, we estimate the parameters of magnetar (i.e., $B_p$ and $P_0$) for given different radiation efficiency, as well as constraining the EOS of NS. It seems that small $P_0$ required by supra-massive magnetar is needed lower radiation efficiency, and estimated $B_p$ of CDF-S XT2 is lower than other typical short GRBs samples for smaller $P_0$. Moreover, we find that three EOSs (GM1, DD2, and DDME2) are consistent with the observational data of CDF-S XT2. Within the second scenario, we constrain the upper limit of ellipticity of NS for given different EOS, it is range of $[0.32 - 1.3] \times 10^{-3}$. By calculating the possible GW radiation for different EOS, we find that its GW radiation cannot be detected by aLIGO or even for more sensitive Einstein Telescope in the future.

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Table 1  The basic parameters of EOS of NS

|       | $M_{TOV}$ | $R$ | $I$  | $\dot{\alpha}$ | $\dot{\beta}$ | $\epsilon$ | $h_c(f)$ |
|-------|-----------|-----|------|-----------------|---------------|-----------|---------|
| BCPM  | 1.98      | 9.94| 2.86 | 3.39            | -2.65         | 1.5       | 3.02    |
| SLy   | 2.05      | 9.99| 1.91 | 1.60            | -2.75         | 1.8       | 2.47    |
| BSk20 | 2.17      | 10.17| 3.50 | 3.39            | -2.68         | 1.3       | 3.34    |
| Shen  | 2.18      | 12.40| 4.68 | 4.69            | -2.74         | 1.2       | 3.87    |
| APR   | 2.20      | 10.0 | 2.13 | 0.303           | -2.95         | 1.7       | 2.61    |
| BSk21 | 2.28      | 11.08| 4.37 | 2.81            | -2.75         | 1.2       | 3.74    |
| GM1   | 2.37      | 12.05| 3.33 | 1.58            | -2.84         | 1.4       | 3.26    |
| DD2   | 2.42      | 11.89| 5.43 | 1.37            | -2.88         | 1.1       | 4.16    |
| DDME2 | 2.48      | 12.09| 5.85 | 1.966           | -2.84         | 1.0       | 4.32    |
| AB-N  | 2.67      | 12.90| 4.30 | 0.112           | -3.22         | 1.2       | 3.71    |
| AB-L  | 2.71      | 13.70| 4.70 | 2.92            | -2.82         | 1.2       | 3.87    |
| NL3ωρ | 2.75      | 12.99| 7.89 | 1.706           | -2.88         | 0.89      | 5.02    |
**Fig. 1** X-ray light curve of CDF-S XT2. The red solid line is the fit with smooth broken power-law model.

**Fig. 2** (a): X-ray plateau luminosity ($L_0$) as function of collapse time ($t_{\text{col}}$) for short GRBs with internal plateau (black dots) and X-ray transient CDF-S XT2 (red diamond). The black solid line is the the best fit with power-law model, and the two dashed lines mark the 2$\sigma$ region of the correlation, respectively. (b) and (c): Distributions of $t_{\text{col}}$ and $L_0$ with best-fit Gaussian profiles, respectively.
Fig. 3  Inferred magnetar parameters, initial spin period $P_0$ vs. surface polar cap magnetic field strength $B_p$ derived for short GRBs with internal plateau (black dots) and X-ray transient CDF-S XT2 (diamond) with $\eta = 0.1, 0.01$ and 0.001. The vertical solid line is the break-up spin period limit for a neutron star (Lattimer & Prakash 2004).

Fig. 4  Collapse time as a function of the protomagnetar mass of CDF-S XT2 for different EOS (color lines). The shaded region is the protomagnetar mass distribution derived from the total mass distribution of the Galactic NSCNS binary systems. The horizontal dashed line is the collapse time in the rest frame.
Fig. 5 Gravitational-wave strain evolution with frequency for CDF-S XT2 with different EOS at distances $D_L = 4480$ Mpc (color lines). The black solid line is the sensitivity limits for ET, and the red and dark cyan solid lines are are the sensitivity limits for aLIGO-Hanford and aLIGO-Livingston, respectively. The data of noise curve are taken from the website: https://git.ligo.org/lcsoft/bilby/-/tree/master/bilby/gw/detector/noise_curves