To investigate the magnetic-field-induced distortion of NSs through GRB X-ray plateaus

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Abstract Magnetic field may distort neutron stars (NSs), but the effect has not been robustly tested through gravitational-wave observation yet due to the absence of a fast rotating Galactic magnetar. The central objects of Gamma-ray bursts (GRBs) could be millisecond magnetars. Under the magnetar scenario on the X-ray plateaus of GRB afterglows, the spindown evolution modulated by the gravitational-wave radiation may be inferred from some special samples, so that the magnetically-induced distorting can be further estimated. According to two samples, GRB 060807 and GRB 070521, we found that the correlation between the effective ellipticity, $\varepsilon_{\text{B,eff}}$, and effective dipole magnetic field strength on a neutron star (NS) surface, $B_{\text{eff}}$, is $\varepsilon_{\text{B,eff}} \sim 10^{-4} \left( \frac{B_{\text{eff}}}{10^{14} \text{G}} \right)^2$. This result demands that $B_{\text{eff}} \sim 0.01 B_t$ with $B_t$ being the internal toroidal magnetic field strength of NSs. We suggested that the torque generated during few unsymmetrical massive-star collapses may induce differential rotations in proto-NSs to amplify the internal toroidal fields.

Key words: gravitational waves – gamma-ray burst: individual (GRB 060807, GRB 070521) – stars: magnetars

1 INTRODUCTION

Rapidly rotating, distorted neutron stars (NSs) are potential gravitational-wave sources. Many authors consider the distortion could be induced by the anisotropic pressure from the internal magnetic field in an NS, especially the internal toroidal magnetic field (Ostriker & Gunn, 1969; Bonazzola & Gourgoulhon, 1996; Konno, Obata, & Kojima, 2003; Ioka, 2001; Palomba, 2001; Cutler, 2002; Ioka & Sasaki, 2004; Stella et al., 2005; Tomimura & Eriguchi, 2005; Haskell et al., 2008; Dall’Osso, Shore, & Stella, 2009; Mastrano et al., 2011). However, this gravitational-wave emission does not show obvious effect in Galactic NSs (Aasi et al., 2014; Abbott et al., 2017a; Gao, Cao, & Zhang, 2017) since these NSs do not maintain strong magnetic field ($> 10^{14}$ G) and fast spin (in LIGO’s range), which are needed to produced a strong gravitational-wave radiation, simultaneously. Soft gamma repeaters and anomalous X-ray pulsars should be corresponding to magnetars (with inferred effective surface magnetic dipole field strength $\sim 10^{14} – 10^{15}$ G, see Rea & Esposito, 2011 for a review), but their spin periods are usually longer than 1 s due to the effective brake by magnetic dipole radiation. Besides, the decay of internal toroidal magnetic field (Li et al., 2016; Beloborodov & Li, 2016; Gao et al., 2019) may also
weaken the distortion. Accretion may accelerate the spin of an NS, but it will induce the decay of the magnetic field in turn (the magnetic field strengths of millisecond pulsars are usually weaker than that of normal pulsars; e.g., Manchester et al. 2005). To test the effect of magnetically-induced distortion through gravitational-wave channel, a fast rotating, strong magnetized NS is needed.

According to the dynamo theory, Duncan & Thompson (1992) shown that a nascent NS with millisecond period would generate an internal magnetic field up to $10^{16}$ G as long as the NS experiences a phase of neutrino-driven turbulent convection. Then the problem is which event can provide such a turbulent condition and tell us there is a millisecond magnetar. Since gamma-ray bursts (GRBs) originate from massive star collapses (Woosley, 1993; Paczynski, 1998; Galama et al., 1998; MacFadyen & Woosley, 1999; Hjorth et al., 2003; Stanek et al., 2003) and NS binary mergers (Paczynski, 1986; Goodman, Dar, & Nussinov, 1987; Eichler et al., 1989; Abbott et al., 2017b), the catastrophes of GRB progenitors may provide such a condition to form millisecond magnetars, i.e., GRB prompt emissions/GRB afterglows are potential events that powered by nascent millisecond magnetars (Usov, 1992; Dai & Lu, 1998a,b; Kluzniak & Ruderman, 1998; Zhang & Meszáros, 2001; Dai et al., 2006; Metzger et al., 2011; Rowlinson et al., 2013). Especially, several GRB X-ray plateaus seem to be only explained reasonably under magnetar scenario (Du, 2020).

Although, so far, it is hard to detect the gravitational-wave radiation from a millisecond magnetar directly (Abbott et al., 2019), under the GRB magnetar scenario, the spindown of the magnetar will record the information of gravitational-wave radiation which may be extracted from the electromagnetic channel (some GRB X-ray plateaus). Therefore, these events may be used to test the effect of magnetically-induced distortion. In this paper, we show the method to infer the magnetically-induced distortion under two assumptions, (i) GRB X-ray plateaus correspond to energy releases of magnetar winds solely behind GRB jets (Du, 2020); (ii) gravitational-wave radiations of magnetars are stimulated by magnetically-induced distortion. The merit of this method is that once the gravitational-wave radiation from the central magnetar of a GRB is detected, the results obtained from gravitational-wave channel and electromagnetic channel can be double checked.

The remaining part of this work is organized as follows. We show our method to estimate the magnetically-induced ellipticity under GRB magnetar scenario in Section 2. We present two-case study of Swift GRB samples, GRB 060807 and GRB 070521, in Section 3. The summary is given in Section 4.

2 THE METHOD

The gravitational radiation produced by magnetic-field-induced distortion depends on the tilt angle between the magnetic and spin axes (Cutler & Jones, 2001). Since the tilt angle can not be determined, as well as the realistic magnetically-induced ellipticity, we introduce an effective magnetically-induced ellipticity, $\varepsilon_{B,\text{eff}}$, so that the luminosity of gravitational radiation is (e.g., Maggiore 2008)

$$L_{gw}(t) = \frac{32GI^2\varepsilon_{B,\text{eff}}^2 \Omega(t)^6}{5c^5}. \quad (1)$$

The other parameters are the gravitational constant $G$, moment of inertia $I$, speed of light $c$ and angular velocity $\Omega(t)$. Similarly, we use an effective dipole magnetic field strength on the NS surface, $B_{\text{eff}}$, to include the deviation from the actual electromagnetic radiation, then the power of spin-down wind is (e.g., Landau & Lifshitz 1979; Shapiro & Teukolsky 1983)

$$L_{\text{em}}(t) = \frac{B_{\text{eff}}^2 R^6 \Omega(t)^4}{6c^3}, \quad (2)$$

where $R$ is the equatorial radius. To connect $\varepsilon_{B,\text{eff}}$ and $B_{\text{eff}}$ and facilitate comparison with theoretic results, we introduce a parameter, $\xi_{\text{eff}}$, that $\varepsilon_{B,\text{eff}} = \xi_{\text{eff}} \left( \frac{B_{\text{eff}}}{10^{14}\text{G}} \right)^2$. Therefore, if the brake is dominated

An alternative ‘powerful contender’ is the fossil field scenario (Ferrario & Wickramasinghe 2006, 2008; see Turolla et al. 2015 for a review).
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by the gravitational radiation, there is

$$\frac{\xi_{\text{eff}}}{(10^{14} \, \text{G})^2} > \sqrt[4]{\frac{5}{192G \, I \Omega_0 B_{\text{eff}}}}$$

(3)

where $\Omega_0 \equiv \Omega(t = 0)$ (similarly hereinafter for the parameter with the subscript 0). Otherwise, the left side of equation (3) should be less than the term on the right.

The next step is to determine what dominates the spindown (see Appendix for more general discussion). As mentioned in the Introduction, GRB X-ray plateaus may be powered by the spin-down winds from their central magnetars. When the magnetic dipole radiation dominates the spindown, i.e., $I \Omega \dot{\Omega} \approx -L_{\text{em}}$, the power of the spin-down wind is

$$L_{\text{em}}(t) = L_{\text{em},0} \left(1 + \frac{t}{\tau_{\text{em}}} \right)^{-2}$$

(4)

where

$$\tau_{\text{em}} = \frac{3c^3 I}{B_{\text{eff}}^2 R^6 \Omega_0^2}$$

(5)

When the gravitational radiation dominates the spindown, i.e., $I \Omega \dot{\Omega} \approx -L_{\text{gw}}$, the power of the spin-down wind is

$$L_{\text{em}}(t) = L_{\text{em},0} \left(1 + \frac{t}{\tau_{\text{gw}}} \right)^{-1}$$

(6)

where

$$\tau_{\text{gw}} = \frac{5c^5}{128GI_{B_{\text{eff}}}^2 \Omega_0^2}$$

(7)

Under the magnetar scenario, GRB X-ray plateaus must track the time evolution of the spin of central NSs (Du, 2020), so that one can derive which mechanism dominates the spindown through the slope of the X-ray light curve following the plateau. However, at this point, we can’t use equation (3) to constrain $\xi_{\text{eff}}$ since the parameters on the right side of this equation are uncertain.

Note that, under the magnetic-dipole-radiation-dominated case, the luminosity of the GRB X-ray afterglow that powered by the spin-down wind should be smaller than the spin-down power itself, i.e.,

$$L_{\text{x}}(t) \leq L_{\text{em}}(t)$$

(8)

and the total energy of the GRB X-ray afterglow that powered by the spin-down wind should be smaller than the rotational energy of the central NS, i.e.,

$$\int_{t_0}^{t_\text{e}} L_{\text{x}}(t) \, dt \leq \frac{1}{2} I \Omega_0^2$$

(9)

As shown in Du (2020), to power an X-ray plateau, the dissipation of the spin-down wind must track the spin-down rate, i.e., the magnetic energy of the spin-down wind should be almost released in X-ray emission totally, so we can approximately equal the left and right sides of equations (8) and (9), respectively. Therefore, the uncertain parameters on the right side of equation (3) can be connected to observable quantities (Du et al., 2019a), i.e.,

$$\Omega_0 \approx \left(\frac{2L_{\text{em},0} \tau_{\text{em}}}{I}\right)^{1/2}$$

(10)
and
\[ B_{\text{eff}} \approx \left( \frac{3c^3I^2}{2\Lambda_{\text{em},0}R^6\tau_{\text{em}}^2} \right)^{1/2}. \]  

(11)

In addition, the power of gravitational radiation decays faster than that of the magnetic dipole radiation (see equations (1) and (2)). When the spindown is dominated by gravitational radiation initially, there will be a moment \( \tau_* \) that the spindown dominated by gravitational radiation will transform into the case of magnetic-dipole-radiation domination [Zhang & Mészáros, 2001; Lasky & Glampedakis, 2016], i.e.,
\[ \tau_* = \frac{\tau_{\text{em}}}{\tau_{\text{gw}}} (\tau_{\text{em}} - 2\tau_{\text{gw}}). \]  

(12)

From equation (12), \( \tau_{\text{em}} \) can be read as
\[ \tau_{\text{em}} = \tau_{\text{gw}} + \sqrt{\tau_{\text{gw}}^2 + \tau_\ast \tau_{\text{gw}}}. \]  

(13)

The extreme sample of this case is that the slope of the X-ray light curve decays as \( 0 \rightarrow -1 \rightarrow -2 \) (see equations (4) and (6)). If there is such a sample, one can obtain \( \tau_{\text{gw}} \) and \( \tau_* \), as well as \( \tau_{\text{em}} \), through data fitting, so that equations (10) and (11) are available and \( \varepsilon_{B,\text{eff}} \) can be directly connected to observable quantities [Du et al., 2019b]. Dividing equation (5) by equation (7), there is
\[ \xi_{\text{eff}}(10^{14} \text{ G})^2 = \sqrt{\frac{5\tau_{\text{em}}}{384\tau_{\text{gw}}G I_0 B_{\text{eff}}}}. \]  

(14)

Substituting equations (10) and (11) into equation (14), there is
\[ \xi_{\text{eff}}(10^{14} \text{ G})^2 = \sqrt{\frac{5\tau_{\text{em}}}{1152G\tau_{\text{gw}}I}}. \]  

(15)

Once \( R \) and \( I \) are obtained from the equation of state (EoS) of NSs, \( \xi_{\text{eff}} \) could be estimated through equation (15).

3 TWO-CASE STUDY

Equation (15) shows \( \xi_{\text{eff}} \) depends on the equatorial radius and moment of inertia of the NS. At present, the EoS of NSs is still uncertain, as well as \( R \) and \( I \) of an NS with known mass. However, observations have provided substantial information to help us choosing appropriate value of parameters, so that the result given by equation (15) keeps rationality.

GRB/type-Ic supernova associations [Galama et al., 1998; Hjorth et al., 2003; Stanek et al., 2003] indicate that long GRBs (duration > 2 s) originate from massive star collapses. According to the mass distribution of the pulsars in Milky Way (see Özel & Freire, 2016 for a review), the mass of the millisecond NS associated with a long GRB could be \( \sim 1.4 \text{ M}_\odot \). The direct measurement of NS masses [Demorest et al., 2010; Antoniadis et al., 2013; Cromartie et al., 2019] and the observations/theoretical studies to the binary NS merger [Abbott et al., 2017b; Margalit & Metzger, 2017; Annala et al., 2018; Hajela et al., 2021] show that the equatorial radius and moment of inertia of a millisecond NS with mass \( \sim 1.4 \text{ M}_\odot \) could be \( R \sim 17 \text{ km} \) and \( I = 3 \times 10^{45} \text{ g \cdot cm}^2 \) [Cipolletta et al., 2018; Riahi et al., 2019].

According to the discussion shown in Section 2 we select two Swift samples (see Figure 1) to fit the data,
\[ F_{\text{ull}} = F \left( \frac{t}{\tau_{\text{gw}}} \omega_{\alpha_1} + \frac{t}{\tau_{\text{gw}}} \omega_{\alpha_2} + \frac{\tau_\ast}{\tau_{\text{gw}}} \omega_{\alpha_2} \left( \frac{t}{\tau_\ast} \right)^{\omega_{\alpha_3}} \right)^{-1/\omega}. \]  

(16)
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Fig. 1: The fitting result of two Swift GRB samples.

Table 1: The fitting result

| Sample     | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\tau_{\text{gw}} (s)$ | $\tau_\star (s)$ |
|------------|------------|------------|------------|----------------------|-----------------|
| GRB 060807 | -0.05      | 1.20       | 2.20       | 5132                 | 36721           |
| GRB 070521 | -0.17      | 0.85       | 2.34       | 362                  | 12894           |

The fitting result is shown in Table 1. According to equations 13 and Table 1, we have $\xi_{\text{eff}}(\text{GRB 060807}) = 5.69 \times 10^{-4}$ and $\xi_{\text{eff}}(\text{GRB 070521}) = 2.47 \times 10^{-4}$. In addition, according to the measured effective surface magnetic dipole fields of Galactic magnetars ($10^{14} - 10^{15}$ G; Rea & Esposito 2011), one can estimate that $\varepsilon_{B,\text{eff}} \sim 10^{-4} - 10^{-2}$.

Our result shows that $\varepsilon_{B,\text{eff}} \sim 10^{-4}(\frac{B_{\text{eff}}}{10^{14} \text{G}})^2$. As a contrast, theoretical work (e.g., Cutler 2002) predicts that the ellipticity, $\varepsilon_B$, induced by the internal toroidal field, $B_t$, satisfies $\varepsilon_B \sim 10^{-4}(\frac{B_t}{10^{14} \text{G}})^2$. If the two conclusions are compatible, there should be a relation that $B_{\text{eff}} \sim 0.01B_t$. This is consistent with the requirement in modeling AXPs/SGRs (Thompson & Duncan 1993, 1995) and the implication of the phase modulation observed for two magnetars (Makishima et al. 2014, 2016) that the internal toroidal fields of magnetars can be up to $10^{16}$ G.

4 SUMMARY

In this paper, we aim at investigating how strong an NS can be distorted by magnetic field. We propose a method to test magnetic-induced distortion of NSs through GRB X-ray plateaus under GRB magnetar scenario. If the distortion is strong enough, the corresponding gravitational radiation can dominate the initial NS spindown and affect the time evolution of the NS electromagnetic radiation, i.e., the decay of GRB X-ray luminosity (with decay index from $\sim 0 \rightarrow 1 \rightarrow 2$). Thus, the ellipticity may be connected to some measurable and inferred parameters. According to the two-case study on GRB 060807 and GRB 070521, we find that $\varepsilon_{B,\text{eff}} \sim 10^{-4}(\frac{B_{\text{eff}}}{10^{14} \text{G}})^2$. To be consistent with the theoretical result, e.g., $\varepsilon_B \sim 10^{-4}(\frac{B_t}{10^{14} \text{G}})^2$, our result shows that there should be $B_{\text{eff}} \sim 0.01B_t$. This deduction could be used as the initial internal magnetic field structure to model the external magnetosphere of an NS.

Large toroidal fields may induce a certain instability for given magnetic configuration (Akgün et al. 2013) and lead to a short-duration magnetar wind under another relation between $B_t$ and $B_{\text{eff}}$, e.g., $B_t = 10B_{\text{eff}}$ adopt in Beniamini & Lu (2021) (so that if $B_t > 10^{10}$ G, there should be $B_{\text{eff}} > 10^{15}$ G which leads to strong brake through magnetic dipole radiation). According to the observation of Galactic magnetars (Rea & Esposito, 2011) and the model-independent constraint on the magnetic field.

2 The afterglows like that of GRB 060807 and GRB 070521 may also be explained as that the transition of the decay slope from $-1$ to $-2$ is just the jet break of the GRB jet with a smaller opening angle (Rhoads, 1999) and the plateau is caused by the jet viewed slightly off-axis (Beniamini et al. 2019).
Fig. 2: The time evolution of $L_{em}$ and $L_{gw}$. The thicker lines correspond to the parameters that $\varepsilon_{B,eff} = 2 \times 10^{-3}$, $B_{eff} = 2 \times 10^{14}$ G, $I = 3 \times 10^{15}$ g·cm$^2$ and $\Omega_0 = 6280$ rad·s$^{-1}$. The thinner lines correspond to the same parameters as that of thicker lines except $\varepsilon_{B,eff} = 5 \times 10^{-4}$.

field for GRB magnetar scenario (Du et al., 2019a), we tend to use $B_{eff} \lesssim 10^{15}$ G as shown above. The larger disparity between $B_{eff}$ and $B_t$ shown in this paper depends on the premise that the early-time evolution of afterglows of GRB 060807 and GRB 070521 are dominated by gravitational-wave radiation and the requirement that our result is consistent with the theoretic predict, i.e., $\varepsilon_B \sim 10^{-4} \left(\frac{B_t}{10^{16} \text{G}}\right)^{2}$. Despite the above uncertainties, strong toroidal fields seem to be inevitable (Ciolfi & Rezzolla, 2013).

Under GRB situation, the possible unsymmetrical collapses and explosions of long GRB progenitors (for the rare cases, e.g., GRB 060807 and GRB 070521) may induce an extra torque which results in differential rotations between the interiors and exteriors of proto-NSs to amplify the internal toroidal fields. In the future, several supermassive star collapses and rare binary NS mergers in $\sim 100$ Mpc may provide changes to test the result shown in this paper (Abbot et al., 2017).

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APPENDIX

To show the general evolution of the spindown, we analytically solve the equation, $I\dot{\Omega} = -L_{em} - L_{gw}$, and get

$$
t = \left[ \frac{\gamma_e}{2\beta^2} \ln \left( \frac{\beta + \gamma_e \Omega(t)^2}{\gamma_e \Omega(t)^2} \right) - \frac{1}{2\beta \Omega(t)^2} \right] \left|_{\Omega_{ho}} \right|_{\Omega},
$$

(17)

Where

$$
\beta = \frac{B_{eff}^2 R^6}{6 I c^3},
$$

(18)

\footnote{Ho (2016) missed $\gamma_e$ in the logarithmic term in his equation (17).}
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\[ \gamma_{e} = \frac{32GI_{5}c_{5}^{2}}{5c^{5}}. \]  

(19)

For comparison, we show two different situations that gravitational-radiation domination initially (thicker lines) and magnetic-dipole-radiation domination initially (thinner lines) in Fig. 2.

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